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13. ABSTRACT (Maximum 200 words)

This study investigated technologies needed for the development of advanced turbine engines (TE) control systems that could improve TE performance and safety and reduce ownership cost. Since such control systems generally consist of one or more sensors, a control system and one or more actuators, this program investigated novel approaches for improved sensing, control and actuation in TE combustors and compressors. A multidisciplinary team of faculty from the school of Aerospace, Electrical and Computer and Mechanical engineering performed this study. Notable accomplishments of this program include: high temperature, wireless MEMS sensors, optical approaches for real time monitoring of combustor efficiency and pattern factor, 3, a "smart" fuel injector for controlling combustor performance, a synthetic jet actuator for improved combustor mixing processes and pattern factor, nonlinear robust and adaptive controllers for combustion and compression systems, a Neural Network Chip for controlling combustion instabilities, LES and CFD for modeling unsteady combustor and compressor flows, respectively, and active control approaches for unstable compressors.

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Sincerely,

Final Report for

A MURI Program Supported Under Army Office of Research
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On

Intelligent Turbine Engines

Prepared by
B. T. Zinn, M. Allen, M. Brooke, A. Glezer, W. Haddad, J. Jagoda,
S. Menon, Y. Neumeier, J.V.R. Prasad, L.N. Sankar and J. Seitzman

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January 31, 2002

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Introduction

This final progress report summarizes the accomplishments of a five-year study entitled Intelligent Turbine Engines that was supported under an Army MURI Grant Number DAAH04-96-1-0008. This program started on November 1, 1995 and terminated on October 31, 2001. The goal of this multidisciplinary research program was to investigate fundamental and practical issues that had hindered the development of active control systems (**ACS**) that could improve the performance of turbine engines (**TE**). Specifically, this program sought to develop the tools needed for TE control systems that could, e.g., increase the range of safe engine operating conditions, reduce fuel consumption at design and off design operating conditions, minimize or eliminate "normal" and unexpected TE failures under steady and highly transient operating conditions, reduce maintenance costs and reduce emissions.

Since a typical ACS generally consists of one or more sensors, a control system and one or more actuators, the development of ACS for TE required a multidisciplinary program. To meet this requirement, the research described in this report was performed by eleven faculty members from the schools of Aerospace (AE), Electrical and Computer (ECE) and Mechanical (ME) engineering, see Figure 1. It provides the names of the program's research team members, their affiliation and expertise. This team investigated active control of compressor and combustor

Name	School	Research Area
Dr. Mark Allen	**ECE**	**MEMS**
Dr. Martin Brooke	**ECE**	**Hardware Neural Networks**
Dr. Ari Glezer	**ME**	**Flow control/actuators**
Dr. Wassim Haddad	**AE**	**Nonlinear control theory**
Dr. Jeff Jagoda	**AE**	**Combustion and spray diagnostics**
Dr. Suresh Menon	**AE**	**LES of reacting flows**
Dr. Y. Neumeier	**AE**	**Control of combustor and compressor processes**
Dr. J.V. R. Prasad	**AE**	**Control of compressor instabilities**
Dr. L.N. Sankar	**AE**	**CFD of compressor flow**
Dr. Jerry Seitzman	**AE**	**Combustion mixing control and sensors**
Dr. Ben Zinn	**AE/ME**	**Control of instabilities and combustion processes**

Figure 1. The Intelligent Turbine Engine research team

processes and enabling technologies that are required for the development of ACS for these components, see Figure 2. The boxes on the left and right of Figure 2 describe specific problems that could be solved/improved by active control of compressor and combustor processes, respectively, and the middle box describes investigated enabling technologies whose advancement would increase the effectiveness of various ACS. These include, e.g., novel sensors, control methodologies for TE components processes described by nonlinear partial differential

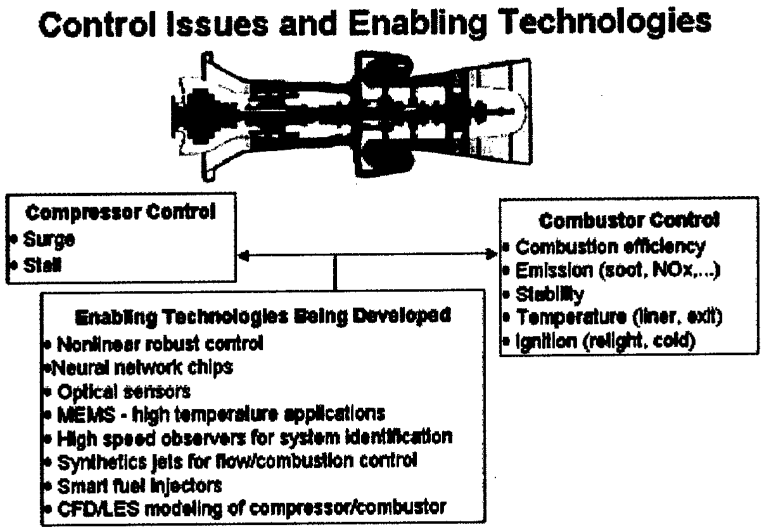

Figure 2. Compressor and combustor problems that could be solved by active control systems and enabling technologies required for these control systems.

equations, actuators for various TE components and development of analytical capabilities for describing the behavior and performance of uncontrolled and controlled TE components

To develop the required control capabilities for FE, this program investigated the following problems:

1. High temperature, wireless MEMS sensors for TE components,
2. Optical approaches for real time monitoring of combustor efficiency and pattern factor*,
3. "Smart" fuel injector for controlling combustor performance,
4. Small-Scale Mixing Enhancement via the Manipulation of Large- and Small Flow Structures with Synthetic jet actuators,
5. Nonlinear Robust and Adaptive Control for Combustion and Compression Systems,
6. Combustion Instability Control with a Neural Network Chip,
7. Development of LES for Single and Two Phase Combustor Flows,
8. CFD of unsteady compressor processes,
9. Manipulation the Pattern Factor Using Synthetic Jets Actuators, and
10. Active control of compressor processes.

*** Studies Nos. 2 and 4 were performed by Dr. Seitzman's team and are described in a single writeup that starts on page 6. Related studies involving other applications of synthetic jets are described under Studies Nos. 4 and 9.**

The objectives and important results obtained under each of these studies are briefly described in the following sections. Since each of these sections describes an independent study, each of these sections may include "its own" list of references, a list of publications that describe the findings of this study, a list of personnel who participated in the study and attained degrees (whenever applicable), and inventions developed under this program.

High temperature, wireless MEMS sensors for TE components

Mark G. Allen

School of Electrical and Computer Science

Statement of the Problem Studied

Intelligent turbine engines require sensing as input for both control algorithms as well as actuator deployment. Variables such as temperature, pressure, and chemical composition are of interest. However, one challenge to the collection of data within the engine is the extremely harsh environment to which the sensors must be exposed. The purpose of this project was to create a sensor, fabricated using microelectromechanical systems (MEMS) technology that could withstand the temperature of the engine and communicate the desired information out of the harsh environment. As a research vehicle, it was decided to fabricate sensors able to measure pressure in the environment of the outlet of the turbine compressor.

Summary of the Most Important Results

In order to withstand the temperature environment at the outlet of the compressor (400-500 C), it was decided to utilize ceramic micromachining technology borrowed from the electronics packaging industry as the major sensor material. To avoid the reliability issues associated with high temperature contacts, as well as to allow the possibility for the sensor to move within the environment of the engine, it was decided to use a wireless approach to read out the pressure data. Since silicon chips and on-board power sources would be unlikely to operate at high temperatures, a passive wireless approach was utilized in which all of the complex electronics required for operation was external to the high temperature environment.

Functional wireless ceramic micromachined pressure sensors operating at 450 °C, with demonstrated materials and readout capability indicating potential extension to temperatures in excess of 600 °C, were designed, fabricated, and tested. These devices were self-packaged and were operated in actual high-temperature environments, not in simulated hot-plate test beds. A resonant readout technique was employed, in which a planar spiral inductor and a pressure-sensitive capacitor form a passive LC circuit, the resonance frequency of which is sensitive to the external applied pressure, and which can be read out using a simple external loop antenna.

More details about this work can be found in the following publications.

List of Publications

Refereed Papers

Fonseca, M., English, J., Von Arx, M., and Allen, M.G., "Wireless Micromachined Ceramic Pressure Sensors," IEEE/ASME Journal of Microelectromechanical Systems, accepted, to appear 2002.

Conference Proceedings

English, J.M., and Allen, M.G., "Wireless micromachined ceramic pressure sensors," Technical Digest, Twelfth IEEE International Conference on Micro Electro Mechanical Systems p.511-16 (1999)

Fonseca, M., English, J.M., Von Arx, M., and Allen, M.G., "High Temperature Characterization of Ceramic Pressure Sensors," Technical Digest, 11^{th} International Conference on Solid State Sensors and Actuators, p. 486-490 (2001)

Technical Reports

English, J., Wireless Micromachined Ceramic Pressure Sensors for High Temperature Environments, Ph.D. Thesis, Georgia Institute of Technology

Listing of Participating Scientific Personnel

Mark G. Allen, Professor, School of Electrical and Computer Engineering

Jennifer M. English, Graduate Research Assistant, School of Electrical and Computer Engineering **(Earned Ph.D. Degree)**

Martin von Arx, Visiting Researcher, School of Electrical and Computer Engineering

Michael Fonseca, Graduate Research Assistant, School of Electrical and Computer Engineering

Report of Inventions

Allen, M.G., and English, J.M., "System, Method, and Sensors for Sensing Physical Properties," **U.S. Patent 6,278,379**

Allen, M.G., and English, J.M., "System and Method for the Wireless Sensing of Physical Properties," **U.S. Patent 6,111,520**

Development of Sensors and Actuators for Active Control of Combustor Processes

Jerry Seitzman

School of Aerospace Engineering

Statement of the problem studied

The work reported here consisted of two main tasks. The first task involved development of sensor approaches for monitoring the state of the combustor exhaust. Specifically, we developed infrared absorption-based sensor approaches for rapidly monitoring gross efficiency and pattern factor. The second major task involved development of: actuators to control fuel-air mixing (in order to improved combustor performance, reduce combustor size, lower pollutant emissions, improve pattern factor, etc.) and diagnostic methods to quantitatively measure fuel-air mixing, especially in evaporating liquid fuel sprays (thereby enabling accurate experiments and comparisons to CFD models).

Summary of the most important results

(a) Sensor Development

A sensor approach for monitoring water mole fraction and temperature uniformity in the exit plane of a high pressure gas turbine combustor was developed. The sensor is based on infrared line-of-sight absorption measurements of water, see Fig. 1. Unlike most sensors previously proposed, the current approach would include the possibility of employing a broadband IR source with a tunable bandpass filter. Prototype sensors were designed for operation in the 2 and 2.5 μm spectral regions, though the general approach is applicable to other wavelengths and absorption species. The sensor performance was simulated using the HITRAN/HITEMP database.

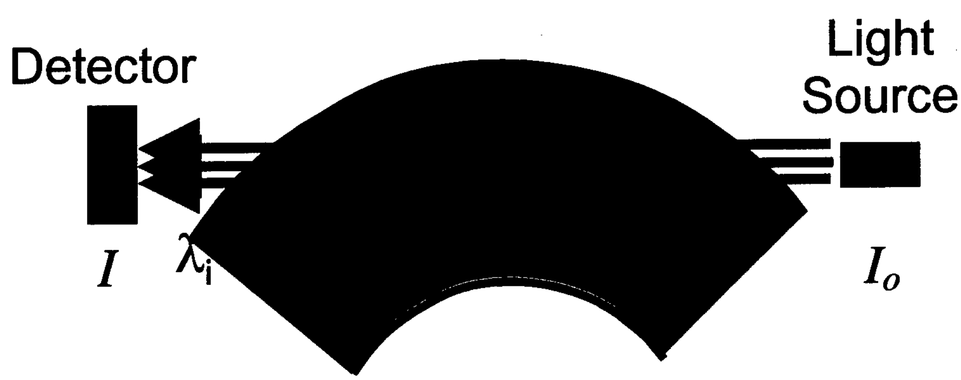

Figure 1. Schematic of absorption sensor deployment for monitoring combustor exhaust conditions in an annular combustor (only partial arc of combustor shown).

The sensor monitors absorption due to water at three wavelengths: one wavelength (λ_I) where the absorption (for a fixed pressure) is linearly proportional to the water mole fraction, but nearly independent of temperature; and two wavelengths where the absorption is monotonically increasing (λ_H) and decreasing (λ_C) with temperature. Thus, absorption measurements at λ_H are more sensitive to the presence of hot gases, while measurements at λ_C are biased towards cold gases. Using these three wavelengths, it was shown that the sensor could determine the water content of high pressure combustor exhaust (and therefore be able to monitor overall combustor health), and the uniformity of the temperature in the gases between the IR source and the detector.

Water Mole Fraction

Since water mole fraction is related to combustion efficiency, a water sensor can be used to quickly identify problems in combustor operation within a sector. Overall water content in the exhaust is monitored at a wavelength with an absorbance that weakly depends on temperature. As shown in Fig. 2, the water mole fraction can be inferred from a simple linear relation between mole fraction and absorbance. In addition, the temperature sensitivity is small enough that the sensor has an accuracy of about 10% over a broad range of temperatures (1000-2000K) and water levels. In the presence of various exhaust profiles, the sensor output tends to fall between the (true) density-averaged and simple path averaged values of water mole fraction. Thus, the sensor could be used in a number of control systems that require a rapid determination of general combustor health.

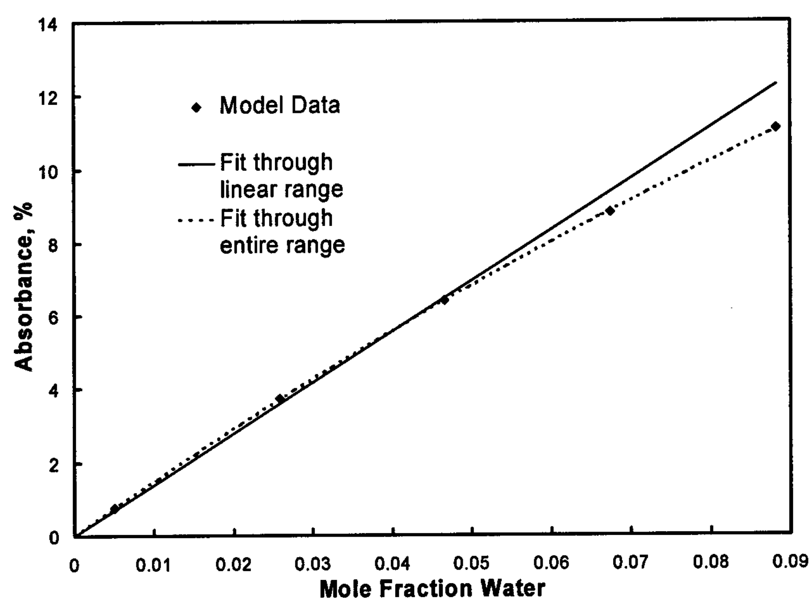

Figure 2. Variation in sensor response (absorbance) with water mole fraction for a broadband light source centered at 4049 cm-1 over 10 cm path with combustor exhaust conditions of 10 atm, 1300 K. The solid line is a best-fit to the data (up to 5% water), while the quadratic fit (dashed line) is over the full range.

Pattern Factor

The temperature uniformity is determined by comparing the temperatures reduced by: 1) using the ratio of the absorption at λ_H to that at λ_I, and 2) the ratio of the absorption at λ_C to that at λ_I. Thus, the sensor can measure two path-averaged temperatures, which agree only when the flow is nearly uniform. The meaningfulness of the difference between these two temperatures is illustrated in Fig. 3. The difference signal (ΔT) is compared to the rms deviation of the temperature profile, for various temperature profiles. The rms deviation was chosen since it scales with the square of the difference between the temperature at a given point and the mean temperature. Thus, it more heavily weights the large temperature fluctuations in the profile, and the largest temperature fluctuations will have a much more significant impact on turbine blade health than small deviations. As seen in Fig. 3, the sensor output (ΔT) scales nearly linearly with the rms of the temperature profiles.

While the approach demonstrated here was for a specific species (water), and a specific set of sensor wavelengths, the same approach could be used with other water lines, or other species, for determining temperature uniformity. In addition, either a broadband or narrowband (e.g., diode laser) source could be used. In an active control system, the sensor output (ΔT, the difference between the two temperatures) would be fed to the controller, which would then try to null the difference between the two inputs, thus producing a more uniform temperature profile for the gases entering the turbine.

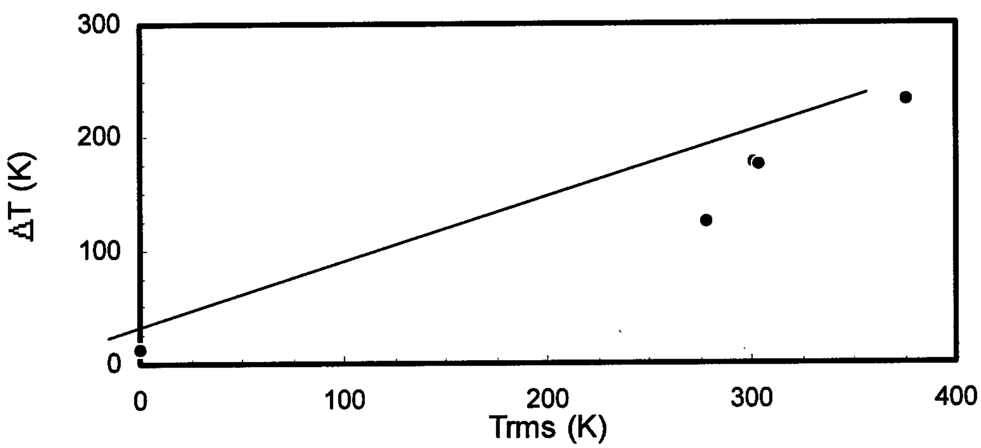

Figure 3. Relationship between the differential sensor output, ΔT, and the rms temperature deviation, Trms, for five temperature profiles having the same average temperature.

(b) Fuel-Air Mixing

Mixing Control Using Synthetic Jets

The traditional approach to control of mixing at the small-scale in most mixing flows has been *indirect*, relying on manipulation of global instability modes of the base flow upstream of mixing transition. However, control of mixing through evolution of large-scale flow structures depends on the classical cascading mechanism to transfer the control influence to the scales at which molecular mixing occurs. Thus, mixing at the smallest scales in fully turbulent shear flows is only weakly coupled to the control input. The present work focused on mixing control based on concurrent manipulation of *both* the small- and large-scale dynamical processes via direct long-range couplings between large- and small-scale motions.

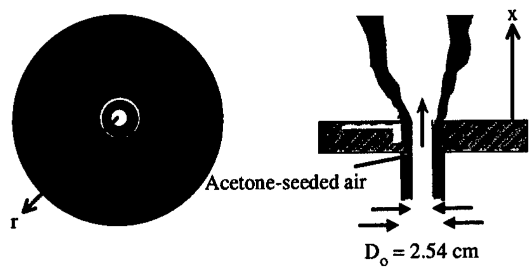

Figure 4. Schematic of the coaxial jet facility with cutaway view of one actuator cavity (the acetone addition is only for the mixing studies).

Quantitative measurements of mixing induced by synthetic jets in gas-gas system were acquired using planar laser-induced fluorescence (PLIF) of acetone (with acetone used as the fuel species). In those experiments, we had fuel in an annular jet mixing with air in a central jet and with ambient air. Nine synthetic jet actuators were placed around the periphery of the outer jet (Fig. 4). Results (Figs. 5-6) showed significant mixing enhancement due to actuation with the synthetic jets, especially when the high frequency (1.2 kHz) synthetic jets are pulsed (amplitude modulated) at lower frequencies (20-100 Hz).

The pulsing produces large-scale structures (see Fig. 7) that enhance entrainment of fuel and air. In that figure, the amplitude modulation duty cycle begins at approximately 80°, which is the phase where small-scale structures first appear near the jet exit. These small-scale structures appear in the later phases when the duty cycle has the actuator active (80°-280°). The large-scale structure is difficult to see at 80°, but is readily apparent at 120°. The pinch in and roll out created by the beginning of the duty cycle propagate downstream at the local flow velocity and create large regions of greatly enhanced mixing. Both the images of Fig. 5 and the deduced amount of unmixed fuel (Fig. 6) show a significant decrease in the flow length required to mix the fuel with the air, a factor of four in the pulsed case compared to the baseline (no actuation) case.

In addition, it was shown that spatial manipulation of the nine actuators could be used to control the fuel patternation. For example, turning on 6 contiguous actuators of the total of 9 present could move most of the fuel to one side of the jet. Thus the present studies showed that synthetic jet actuation could be used to enhance both large- and small-scale mixing *when needed*, and control fuel patternation.

Mixing Measurements in Liquid Fuel Systems

While numerous studies have examined acetone (and other ketones) for measuring fuel vapor concentration in gaseous systems (such as those presented above), little quantitative work has been performed in two-phase flows, i.e., evaporating sprays, to simultaneous measure the vapor concentration and droplet size using the simplicity of a single laser and single camera. This was the focus of the effort reported here.

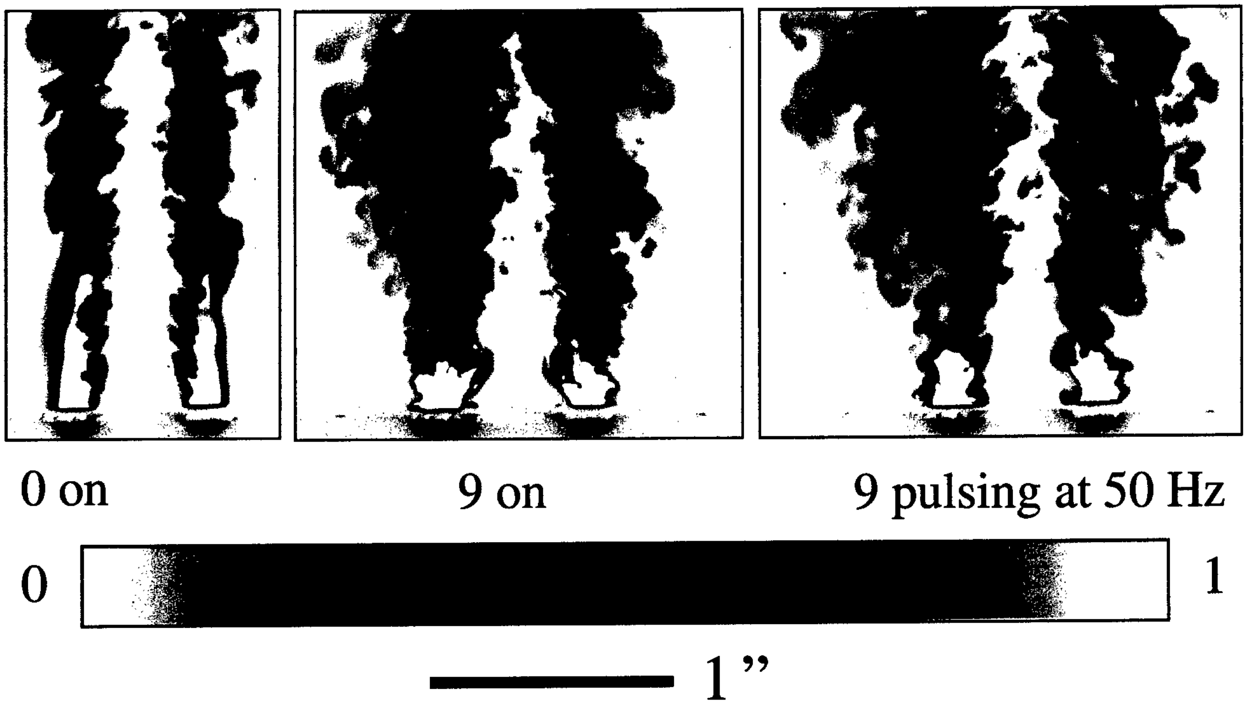

Figure 5. Sideview images of the coaxial, turbulent jet flow using PLIF of acetone seeded in the outer (annular) jet. Images without mixing enhancement (left), with all 9 synthetic jets on (middle), and with 50 Hz amplitude modulation applied (right). The color bar shows the scaling of mixture fraction from 0 (pure air) to 1 (pure annular jet fluid). Also shown is a 1-inch spatial scale.

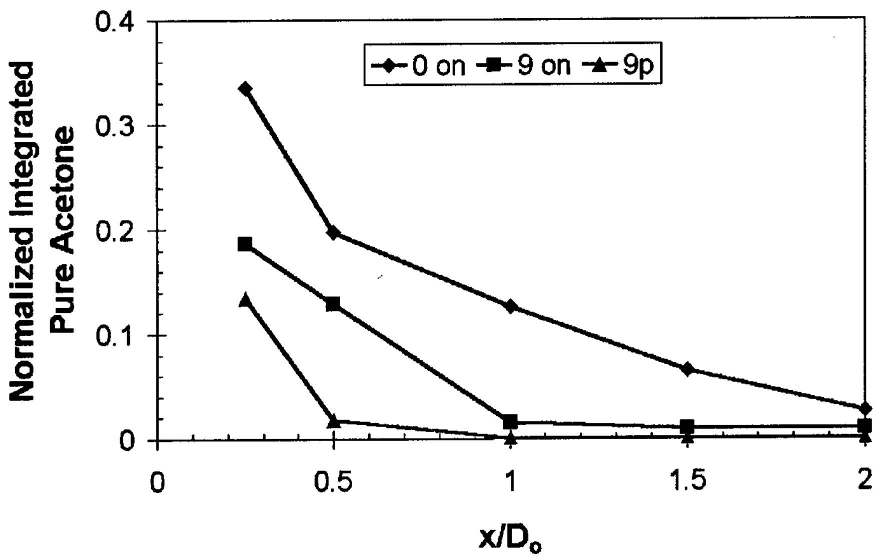

Figure 6. Axial variation of the radially and azimuthally integrated “pure” fuel (mixture fraction $f \geq 0.95$), 0 on signifies no actuation, 9 on signifies actuation of all nine synthetic jets without amplitude modulation, 9p signifies actuation of all nine synthetic jets with amplitude modulation.

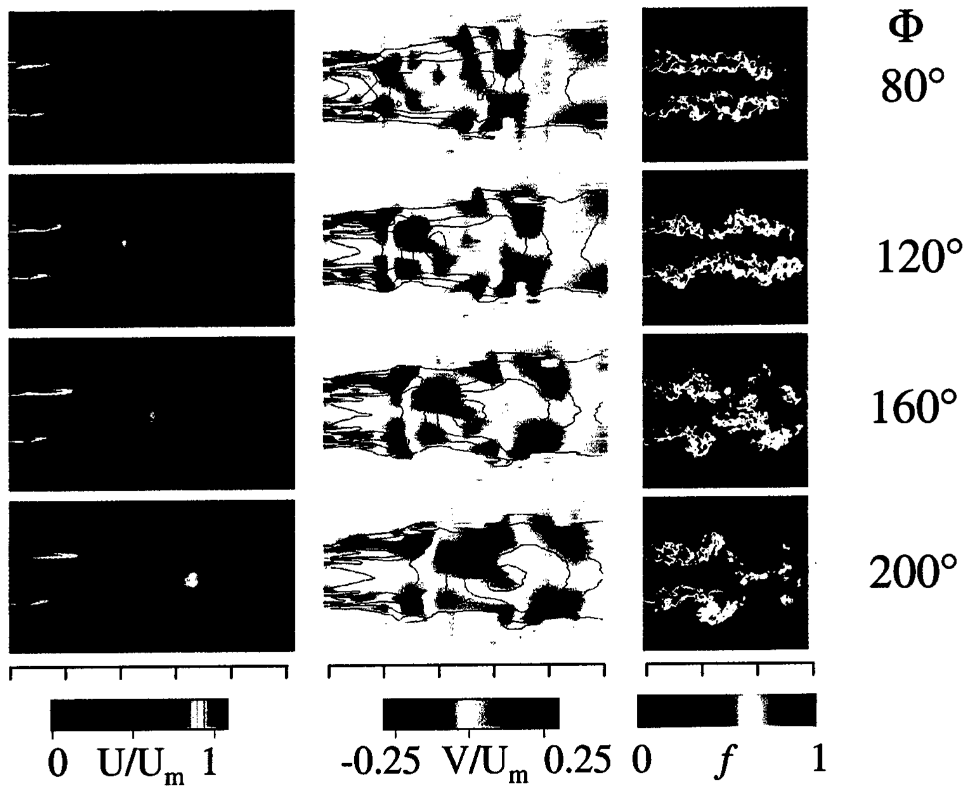

Figure 7. Axial velocity (left), radial velocity (middle) and scalar mixture fraction images of the coaxial mixing jet for amplitude modulated actuation at 4 phases in the modulation cycle. (Flow is left to right in these images.)

A key to making quantitative LIF measurements in multiphase flows is distinguishing between the signals coming from the different phases. While droplets sufficiently larger than a pixel can be resolved geometrically, phase discrimination is an issue for subpixel sized droplets. This is typically the situation since pixel resolutions in practical flows are usually limited to 100 μm or greater, and droplet sizes are often below 100 μm. Since both phases of acetone (and other ketones) fluoresce over essentially the same spectrum, the phases cannot be readily distinguished spectrally. However, the large density difference between the phases leads to a possible solution. The higher density of liquid acetone (~750× the vapor density at standard conditions) results in much larger signals from droplets compared to vapor of the same volume. Thus, signal strength can be used to discriminate fluorescence from vapor fuel and liquid droplets larger than some minimum critical diameter, i.e., when the fluorescence from the liquid exceeds the fluorescence from a measurement volume (associated with a single pixel) that is filled with saturated acetone vapor.

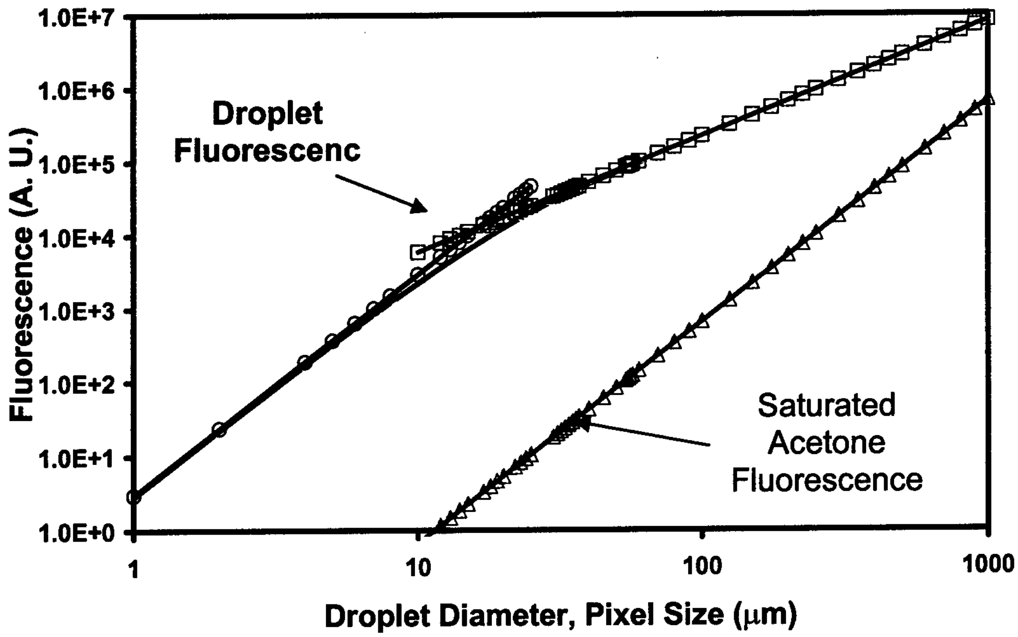

Figure 8. Fluorescence power versus droplet diameter for liquid acetone and versus pixel size for saturated vapor at room temperature. Calculations assume 266 nm laser light, square pixels, and standard pressure.

A model of the liquid and vapor fluorescence signals that includes laser extinction in a droplet due to absorption, refraction and reflection was developed for distinguishing between the fluorescence from droplets and from vapor. The model results were used to determine cutoff diameters for a standard set of experimental parameters, such as laser wavelength (266 nm) and air temperature (300 K). The results, illustrated by an example condition shown in Fig. 8, indicate that rather small droplets can be discriminated from gaseous fuel. For example, a 20 μm droplet will produce more fluorescence than a 170 μm pixel filled with saturated acetone vapor. Such a technique would be convenient for comparison with CFD model results, where fuel droplets are tracked until they reach a minimum size, after which time they are considered to evaporate immediately.

For simultaneous, quantitative measurements of droplet size (for subpixel sized droplets) and vapor concentration (or mixture fraction) in a plane, we also developed a single laser, single camera technique that relies on temporal discrimination of the liquid and vapor signals. The approach is based on the fact that liquid acetone, excited by a uv laser, produces both a short-lived (~10 ns) fluorescence signal and a long-lived phosphorescence. The corresponding phosphorescence from the vapor is completely quenched by collisions with oxygen molecules.

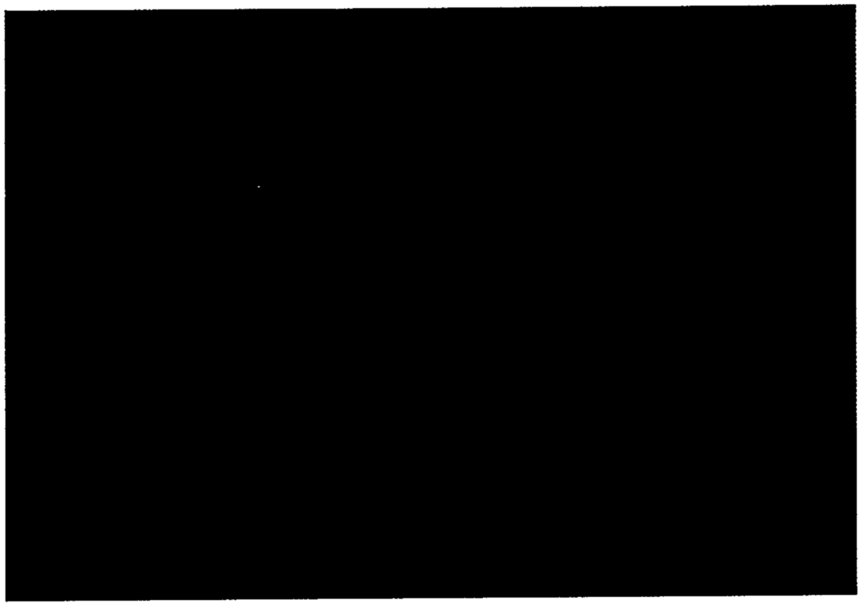

Figure 9. Long exposure image of evaporating spray taken with the laser sheet perpendicular to the main spray axis (flow is out of the paper). Vapor as seen as near continuous regions, while individual droplets are seen as bright streaks. For droplets in the left side of the image, the motion is generally toward the bottom left of the image (which represents a radial motion away from the center of the flow and toward the viewer, since the image plane was oriented ~40° to the laser sheet).

In order to employ the technique, we measured the characteristic lifetime of *liquid* acetone droplets in an evaporating spray. The results gave a lifetime of ~200 μs, about the same as for unquenched vapor. The ratio of the total phosphorescence to fluorescence for the liquid was found to be 8, i.e., integrated over time, the phosphorescence signal is almost 10 times greater than the fluorescence from the liquid. In order to measure both liquid and vapor concentration, an interline camera is used to acquire two images from a single laser pulse: a short exposure image (e.g., 1 μs exposure) to capture the fluorescence (but very little phosphorescence), and then a long exposure image to capture the phosphorescence. The phosphorescence, which results only from the liquid phase, can be converted into droplet diameters. Then by subtracting the proportional amount of liquid fluorescence from the first image, the vapor fluorescence/concentration is found. In addition, the short exposure image should be free of streaks, making data analysis easier. Finally, velocity information can be extracted from the streaked image produced as the droplet moves during the second exposure (see Fig. 9). Using the measured phosphorescence lifetime, the characteristic signal decay length along the streak can be converted to a velocity. For the image shown in Fig. 9 (where the camera's image plane is at an angle to the laser sheet), the measured droplet axial velocity components are ~3-4 m/s, about what the velocity of the coflowing gas jet is at this region.

List of Publications

Refereed

J. M. Seitzman and B. T. Scully, "Broadband Infrared Absorption Sensor for High Pressure Combustor Control," Journal of Propulsion and Power **16**, No. 6, pp. 994-1001 (2000).

Non-refereed

B. D. Ritchie and J. M. Seitzman, "Simultaneous Droplet Size and Mixture Fraction Using Acetone PLIF," paper AIAA-2002-0826 at the 40th AIAA Aerospace Sciences Meeting, Reno, NV, January 14-17, 2002.

B. D. Ritchie and J. M. Seitzman, "Quantitative Acetone PLIF in Two-Phase Flows," paper AIAA-2001-0414 at the 39th AIAA Aerospace Sciences Meeting, Reno, NV, January 8-11, 2001.

Glezer, J. Seitzman, S. Edlund and B. Ritchie, "The Manipulation of Small-Scale Mixing in Coaxial Jets Using Synthetic Jet Actuators," 8th European Turbulence Conference ETC8, Spain, July 2000.

B. Ritchie, D. Mujumdar, and J. Seitzman, "Controlled Fuel-Air Mixing Using a Synthetic Jet Array," paper AIAA-2000-3465 at the 36th AIAA/ ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, AL, July 16-19, 2000.

B. T. Zinn, M. G. Allen, A. Glezer, J. I. Jagoda, Y. Neumeier, and J. M. Seitzman, "Active Control of Combustor Processes," at NATO/RTO, Braunschweig, Germany, May 8-12 2000.

B. D. Ritchie, D. R. Mujumdar and J. M. Seitzman, "Mixing in Coaxial Jets Using Synthetic Jet Actuators," paper AIAA-2000-0404 at the 38th AIAA Aerospace Sciences Meeting, Reno, NV, January 10-13, 2000.

B. D. Ritchie and J. M. Seitzman, "Mixing Control of Fuel Jets Using Synthetic Jet Technology: Scalar Field Measurements," paper AIAA-99-0448 at the 37th AIAA Aerospace Sciences Meeting, Reno, NV, January 11-14, 1999.

B. T. Scully and J. M. Seitzman, "Water Based Infrared Sensor for Control of Turbine Engine Combustors," paper AIAA-99-0517 at the 37th AIAA Aerospace Sciences Meeting, Reno, NV, January 11-14, 1999.

J. M. Seitzman, R. T. Wainner and R. Tamma, "Diagnostics and Sensors for Turbine Engines," paper LWA1 at the Laser Applications to Chemical and Environmental Analysis Topical Meeting of the Optical Society of America, Orlando, Florida, March 9-11, 1998.

B. D. Ritchie and J. M. Seitzman, "Acetone Fluorescence Measurements of Controlled Fuel-Air Mixing," paper AIAA-98-0350 at the 36th AIAA Aerospace Sciences Meeting, Reno, NV, January 12-15, 1998.

J. M. Seitzman, R. Tamma and B. T. Scully, "Broadband Infrared Sensor for Active Control of High Pressure Combustors," paper AIAA-98-0401 at the 36th AIAA Aerospace Sciences Meeting, Reno, NV, January 12-15, 1998.

K. Aung, S. Liang, J. Seitzman, and J. Jagoda, "Measurements of Spray Properties and Mixing in a Simulated Combustor," paper AIAA-98-0717 at the 36th AIAA Aerospace Sciences Meeting, Reno, NV, January 12-15, 1998.

B. D. Ritchie and J. M. Seitzman, "Acetone Imaging for Measurement of Enhanced Mixing from a Fuel Injector," paper AIAA-97-2380 at the 28th AIAA Plasmadynamics and Lasers Conference, Atlanta, GA, June 23-25, 1997.

J. M. Seitzman, R. Vijayan and R. Tamma, "Infrared Absorption Based Sensor Approaches for High Pressure Combustion," paper AIAA-97-0318 at the 35th Aerospace Sciences Meeting, Reno, NV, January 6-9, 1997.

Conference Presentations

B. Ritchie and J. Seitzman, "Controlled Fuel-Air Mixing Using Synthetic Jets," paper W1G07 at Twenty-Seventh Symposium (International) on Combustion, Boulder, CO, August 2-7, 1998.

Manuscripts submitted, but not published

S. Davis, B. Ritchie, A. Glezer and J. Seitzman, "Enhanced Mixing of a Round Jet Induced by Synthetic Jets," Physics of Fluids.

B. D. Ritchie and J. M. Seitzman, "Simultaneous Droplet Size and Vapor Concentration Imaging Using Acetone PLIFP

List of all participating scientific personnel

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"Smart" Liquid Fuel Injector for Active Control of Combustor Processes

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Study Objective

The objective of this research was to develop a "smart" liquid fuel atomizer that could be actively controlled to provide a fuel spray with desired properties over a wide range of operating conditions of airborne gas turbines. Such an injector would overcome the shortcomings of the state-of-the-art pressure and air-blast atomizers that produce poor sprays during some operating conditions; e.g., startup and idling. Furthermore, active control of fuel droplet size at any desired fuel flow rate during a flight can be used to control UHC, NOx and CO emissions [0], [0]

Main results

A preliminary study of available liquid fuel atomizer had concluded that an internally mixed liquid fuel atomizer offered the best potential for real time control of the generated spray properties. A schematic of the investigated internally mixed atomizer is shown in Fig. 1. Liquid fuel is axially supplied to the atomizer at its upstream end and air is injected through series of holes symmetrically distributed around the injector's periphery downstream of the liquid entry point. As the air expands within the injector and occupies an increased fraction of the available cross sectional area, the cross sectional area available to the liquid is reduced. This is accompanied by acceleration of the liquid phase and, thus, an increase in its kinetic energy, which leads to liquid atomization. Also, the relative motion between the phases produces shear forces at their interfaces that "strip" liquid droplets from liquid ligaments, resulting in further liquid atomization. Together, these processes produce a mixture of liquid ligaments and droplets and air inside the injector.

The performance of the developed injector has been investigated in an experimental setup specifically developed for this purpose. It consists of a vessel, with windows, that can be operated over a wide range of pressures. The injector was installed at the top of the vessel and the injected liquid was collected at the bottom. The windows provide optical access for determining the properties of the spray. Series of tests were conducted to determine the dependence of the spray properties upon the amount of atomizing air, the liquid supply pressure and the test chamber pressure. This study also sought to determine the mode of operation that would permit control of the characteristics of the generated spray.

A performance map of the investigated injector is shown in Fig. 2. It shows the dependence of the Sauter Mean Diameter (SMD) of the generated spray upon the liquid flow rate and supply pressure. It should be noted that in these experiments the liquid flow rate was controlled by varying the flow rate of atomizing air. The data in Fig. 2 show that by varying the liquid supply pressure while keeping the liquid flow rate constant, i.e., moving along the vertical line in Fig. 2, which requires variation of the air flow rate, one can vary the droplet sizes while keeping the liquid flow rate constant. Figure 2 also shows that simultaneously changing the liquid supply pressure and flow rate (again, by varying airflow rate) while moving along the horizontal line in Fig. 2 permits operation with a constant droplet size over a range of liquid flow rates. Thus, for a given combustor pressure, the injector's performance can be controlled by changing the airflow rate and the liquid supply pressure simultaneously.

In parallel efforts, a model for predicting the performance of the above-described injector was developed. The objective of this study was to obtain an analytical tool that could be applied in the design of improved internally mixed injectors and to predict the injector's flow and spray characteristics, e.g., the liquid flow rate and mean droplet size, under different operating conditions. The developed two phase flow model assumed that the flow is one-dimensional, wall friction is negligible, the liquid flow is isothermal incompressible, the flows are uniform and steady and the air behaves as a perfect gas. Also, the airflow injection ports are approximated by an annular slit of a finite width at the injector's wall. Finally, it has been also assumed that as the two phase flow evolves, the liquid break ups into droplets in a manner that maintains the local Weber number ($We = \rho_a V_r^2 D/\sigma$; i.e., the ratio of the inertial and surface forces) at a value of 10 and that the droplets do not coalesce to form larger droplets. An advance model which account for droplet size distribution, coalescence and secondary droplet breakdown was developed using probabilistic value for the Weber number and keeping account for the droplets sizes.

The model's system of equations that govern the two-phase flow in the injector's passage are the air mass conservation, liquid mass conservation, combined air and liquid momentum conservation, combined air and liquid energy conservation and liquid energy conservation. The interaction between the phases, which appears only in the liquid energy equation, is modeled as a drag force acting on the liquid. These equations were solved numerically to determine various flow and spray properties inside the injector.

Figure 3 compares the predictions of the model with measured data. Figures 3a and 3b, which compare measured and predicted liquid flow rates and mean droplet diameters, respectively, show that the model provides reasonable predictions of the performance of the complex injector flow.

In summary, the results obtained to date strongly suggest that the developed, internally mixed, atomizer can be used to control liquid fuel spray properties in TE combustors. Such control can be attained by simultaneously varying the liquid supply pressure and air flow rate. The developed theoretical model can be used to optimize the design of such an injector and as a module in gas turbine simulation.

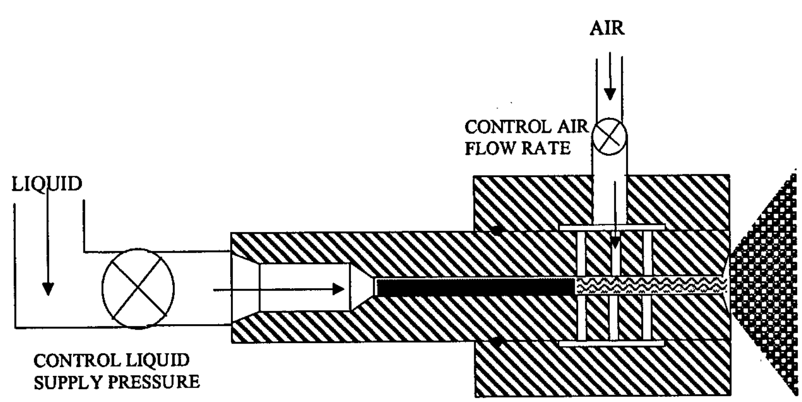

Figure 1. A schematic of the investigated internally mixed atomizer.

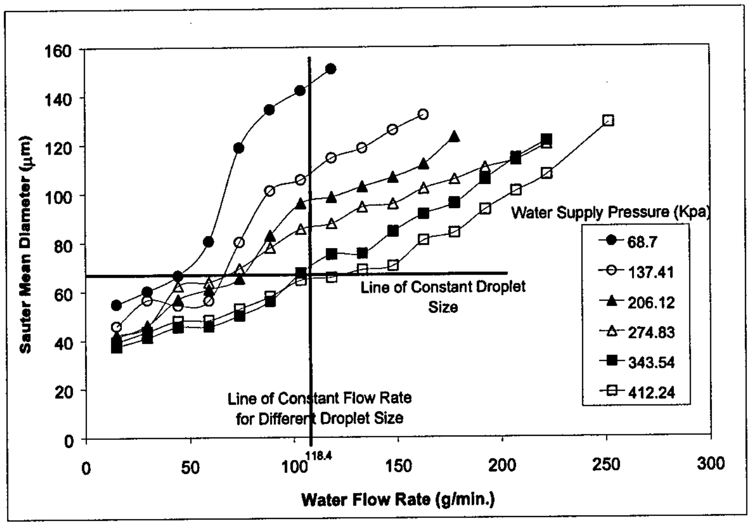

Figure 2. Performance map of the tested atomizer.

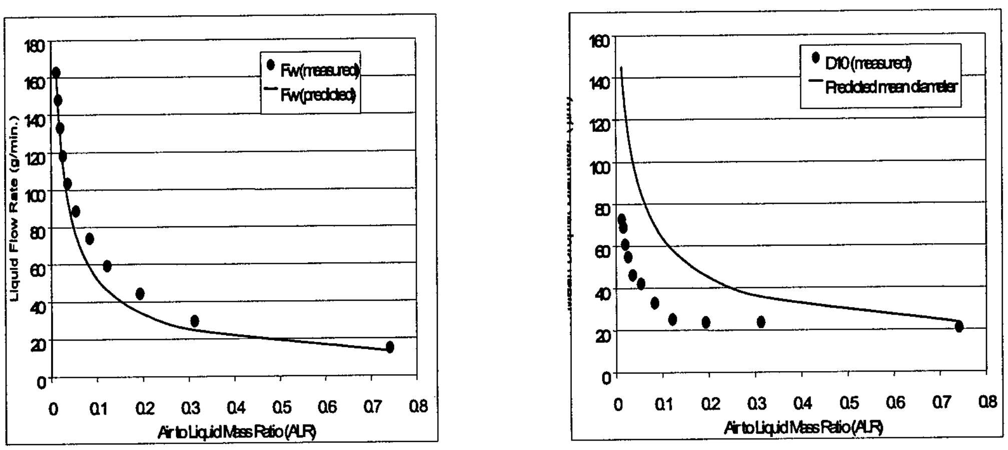

Figure 3. Comparison of theoretical and experimental values of (a) liquid flow rate and (b) drop size.

List of Publications

Refereed

A. Kushari, Y. Neumeier, O. Israeli, E. Lubarsky and B. T. Zinn, "Internally Mixed Liquid Injector for Active Control of Atomization Process", *Journal of Propulsion and Power*, Vol. 17, No. 4, July-August 2001, pp. 878-882.

A. Kushari, Y. Neumeier and B. T. Zinn, "A Theoretical Study of an Internally Mixed Liquid Atomizer", submitted for publication in *AIAA Journal of Propulsion and Power*.

Non-refereed

A. Kushari, Y. Neumeier, E. Lubarsky and B. T. Zinn, "Study of Liquid Atomization in an Internally Mixed Liquid Atomizer", *ASME Turbo Expo – 2001, Land, Sea and Air*, June 2001, New Orleans, LA.

A. Kushari, Y. Neumeier, E. Lubarsky and B. T. Zinn, "Effect of Injector Geometry on the Performance of an Internally Mixed Liquid Atomizer", AIAA 2001-0329, *39th AIAA Aerospace Sciences Meeting and Exhibit*, Jan. 2001, Reno, NV.

A. Kushari, Y. Neumeier, E. Lubarsky and B. T. Zinn, "Heuristic Modeling of Two-Phase Gas-Liquid Flow in an Internally Mixed Liquid Atomizer", AIAA 2000-3493, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 17-19, 2000, Huntsville, Alabama.

A. Kushari, Y. Neumeier, E. Lubarsky and B. T. Zinn, " A Theoretical Investigation of the Performance of an Internally Mixed Liquid Atomizer", AIAA 2000-1021, *38th AIAA Aerospace Sciences Meeting and Exhibit*, Jan. 2000, Reno, NV.

A. Kushari, Y. Neumeier, O. Israeli, A. Peled and B. T. Zinn, " An Internally Mixed Injector for Active Control of Atomization Process in Liquid Fueled Engines", AIAA 99-0329, *37th AIAA Aerospace Sciences Meeting and Exhibit*, Jan. 11-14, 1999, Reno, NV.

Reports

Kushari, Abhijit, "Study of an Internally Mixed Liquid Injector for Active Control of Atomization Process," Ph.D. Thesis, Georgia Institute of Technology, August 2001.

Scientific Personnel

Dr. Kushari, a Ph.D. graduate student earned a M.S. and a Ph.D. while working under this program.

Dr. Y. Neumeier, Senior Research Engineer

Dr. E Lubarsky Senior Research Engineer

Dr. B. T. Zinn, Regents' Professor and project PI.

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Small-Scale Mixing Enhancement in Air Jets via the Manipulation of the Large- and Small-Scale Flow Structures with Synthetic Jet Actuators

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Statement of the problem studied

Control of the mixing of fuel and oxidizer in a combustor is necessary for high combustion efficiency, combustor stability, and low emissions. The traditional approach to control of mixing at the small-scales in free shear flows has been *indirect* and has relied on manipulation of large-scale, global instability modes of the base flow upstream of mixing transition. The control influence is transferred to the scales at which molecular mixing occurs by means of the classical cascading mechanism.

The goal of the present work was to demonstrate more efficient control of mixing in turbulent shear flows by ***direct control of both the large-scale entrainment and the small-scale mixing*** processes. To this end, the present work focused on an investigation of the flow field of single and coaxial round jets in which both the small- and large-scale motions were concurrently manipulated. This was accomplished by exploiting long-range couplings affected at the small scales using high-frequency, time modulated actuation. Another goal of the present work was to quantify the improvement in scalar mixing using laser induced fluorescence of acetone vapor in an identical jet facility. The actuation was effected using azimuthal arrays of synthetic jet actuators placed near the jet exit plane.

Summary

Control of mixing in plane and ax symmetric shear layers through evolution of the large-scale vortical structures depends on the classical cascading mechanism to transfer the control influence to the scales at which molecular mixing occurs. Thus, mixing at the smallest scales in fully turbulent shear flows is only weakly coupled to the control input. More efficient control of mixing in fully turbulent shear flows might be achieved by direct (rather than hierarchical) control of both the large-scale entrainment and the small-scale mixing processes. The present work focuses on mixing control based on concurrent manipulation of both the small- and large-scale dynamical processes via direct long-range couplings between large- and small-scale motions in axisymmetric shear layers. The concept of long-range interactions between widely disparate scales in turbulent flows (Yeung, Brasseur, & Wang, 1995) was demonstrated in the experiments of Wiltse & Glezer (1993) who achieved small- to large-scale coupling by exciting discrete wave numbers within the dissipation range of a jet shear layer using cantilevered piezoelectric actuators. In a more recent work, Wiltse & Glezer (1998) showed that direct excitation of the small-scales leads to an increase in dissipation and energy transfer from large-scales to small-scales, even when the mean distributions of velocity and rms velocity fluctuations are unchanged.

In the present work, the shear layers of coaxial round jets are forced using an azimuthal array of synthetic jet actuators (zero net mass flux, e.g., Smith & Glezer, 1997, 1998) placed around

the perimeter of the jet nozzle. These jets are synthesized by a train of vortical structures that form at an orifice bounding a small sealed cavity, typically by the motion of a membrane in one of the cavity walls. The scale of these vortical structures can be adjusted to match and directly interact with the small-scale eddies within the equilibrium range of the embedding flow. Previous experiments in a single round jet with the same forcing scheme showed dramatic effects on the structure of the jet mixing layer and small-scale mixing (Davis & Glezer 1999) and Ritchie & Seitzman 1999). High-frequency excitation resulted in larger cross-stream spreading of the jet shear layer and increased entrainment in the jet near field ($x / D < 1$), and amplitude modulation of the excitation waveform resulted in the formation of large-scale vortical structures and a two-fold increase in entrainment.

Small-scale motions and mixing processes within the shear layers of single and coaxial round jets are enhanced by direct excitation of the large- and small-scale flow structures using a high-frequency carrier waveform with varying degrees of spatial and temporal modulation. The carrier frequency is selected to be within the equilibrium range of the ensuing flow and well above the unstable frequencies of the jet column. The coaxial jets are operated in two modes, namely wake-like (where the velocity of the inner jet is lower) or jet-like (where the velocity of the inner jet is higher). The excitation is effected using an azimuthal array of individually addressable synthetic jet actuators placed around the perimeter of the jet nozzle. The actuators are operated at resonance which is the carrier frequency of the excitation waveform. The primary diagnostic tool of the present work is hot-wire anemometry (both single and two-component). Some measurements of mixing are obtained using planar laser-induced fluorescence.

High-frequency forcing results in spectral peaks within the equilibrium range of the jet shear layers (both inner and outer shear layers for coaxial jets) at the carrier resonance frequency of the actuators (nominally 1200 Hz) and some of its higher harmonics. It is important to note that velocity spectra within the potential flow outside of the shear layers (immediately downstream of the jet exit plane) quickly develop a broad band of high frequencies (and small-scales) that are typical of turbulent flows. The amplitude of the spectral peak at the forcing frequency decreases with downstream distance, but remains discernible from the background flow throughout the measurement domain. Despite the addition of energy to the flow through the action of the forcing, the turbulent kinetic energy (of the streamwise velocity component) in the forced flow is lower compared to the unforced flow by $x / D \simeq 3$ in both the single and coaxial jets, as a result of increased small-scale dissipation.

Unmodulated, axisymmetric excitation in the single jet leads to radial spreading of the jet and a decrease in the streamwise velocity. (The centerline velocity decreases by 10% within the first jet diameter.) In the coaxial jets, high-frequency forcing results in radial spreading of the annular flow toward the ambient (and away from the core flow) irrespective of the velocity ratio and thus results in an increase in the low velocity wake region in the near-field downstream of the center tube. The radial velocity is especially important in the coaxial flows for mixing of the two streams because it is a measure of radial penetration between the two flow domains. Unmodulated high-frequency forcing is most effective near the jet exit plane where it results in radial flow oscillations in the inner shear layer at the actuators' resonance frequency and the formation of vortical structures in the mixing region. Small-scale motions are increased in both primary jet configurations (i.e., single and coaxial) in the near field ($x / D < 1$). Data from measurements in the coaxial jet show that both production and dissipation increase with forcing over this streamwise domain. In both the single and coaxial jets, the rms streamwise velocity fluctuations u' are lower in the high-frequency forced flow than in the unforced flow for $x / D \gtrsim 1$. The lower values of u' result from increased dissipation upstream and decreased production downstream in the forced flow. As a result of the streamwise reduction in velocity fluctuations, it is expected that small-scale mixing is primarily enhanced within the near field of the jet exit plane.

Mixing enhancement is assessed from PLIF images of acetone concentration. In the single jet flow the PLIF images reveal the size and shape of the mixing region and the quantity of pure jet fluid remaining. In the coaxial jets the PLIF images show the decrease in the volume of pure air within the jet core of the forced flow that is accompanied by a decrease in the volume of pure acetone in the annular flow. The data from both configurations show good qualitative agreement between concentrations of small-scale motions (as measured by u') and regions of increased mixing. The mixed fluid fraction calculated from data in the single jet indicates a decrease in mixing enhancement with streamwise distance as expected from the velocity data.

Azimuthally-periodic forcing having a three-fold symmetry using either a radial or axial forcing configuration is investigated in the single jet flow. The three-fold symmetry of the forcing results in a corresponding three-fold symmetric distortion of the primary jet cross section. Radial forcing and streamwise (axial) forcing configurations result in either lobe-like or triangular jet cross sections, respectively. In both cases the length of the shear region in cross stream planes of the primary jet increases substantially (35% and 56% at $x / D = 1$ in the radial and axial modes, respectively). The increase in small-scale motions along the lobes of the radially forced primary jet indicates that small-scale mixing between the jet and ambient fluids can be enhanced if the lower-speed fluid protruding between the lobes can be efficiently entrained from the domain outside of the radial edge of the primary jet. PLIF images acquired in cross stream planes show that mixing occurs primarily in these regions of large velocity fluctuations. The current radial configuration is not particularly efficient in entraining ambient fluid into the low velocity regions and thus does not significantly improve mixing. PLIF images of the axial forced flow with three-fold symmetry indicate that the outward radial protrusions of the primary jet shear layer into the ambient fluid enhance mixing.

Overall entrainment of fluid across the jet streams in both the single and coaxial jets is modified by introducing large-scale vortical structures into the jet shear layers concomitantly with direct small-scale excitation. The vortical structures are induced over a broad range of frequencies by amplitude modulation of the high-frequency excitation waveform of the actuators. Power spectra of the streamwise velocity show that amplitude modulation of the excitation waveform results in the appearance of spectral peaks at the modulation frequency and its higher harmonic with sidebands around the resonance frequency. The spectral peaks at the modulation frequency at the low end of the spectrum undergo strong amplification on the jet centerline within the domain $x / D < 1$. Although the actuation energy is lower with modulation of the excitation waveform (due to the modulation duty cycle), modulation results in higher turbulent kinetic energy compared to unmodulated forcing due to the amplification of the modulation frequency and its higher harmonics.

The effect of the modulation frequency is assessed using triple decomposition of the jet centerline velocity that is measured phase-locked relative to the modulating waveform. The primary effect of the modulation frequency is to increase the magnitude of the coherent fluctuations $\tilde{u}$ while the mean velocity U and incoherent velocity fluctuations u' are relatively insensitive to the modulation frequency. Although the streamwise amplification rate of $\tilde{u}$

increases with modulation frequency, the induced velocity fluctuations at high frequencies saturate and begin to decay closer to the jet exit plane. The broadband amplification of $\tilde{u}$ suggests that the amplification is independent of the natural instabilities of the shear layer (or layers) of the base flow and that these instabilities are probably bypassed by the forcing. The insensitivity of u' to modulation of the high-frequency excitation waveform suggests that there is no significant coupling between the low frequency forcing and the small scales.

Extensive measurements of the velocity and scalar field are acquired at a given modulation frequency for each of the primary flow configurations (40 Hz with an effective duty cycle of 0.67 in the single jet and 60 Hz with a duty cycle of 0.6 in the coaxial jets). Two component velocity distributions in the near field of the jet that are acquired phase-locked to the modulation waveform reveal that the transients associated with the square wave modulation lead to the formation of discrete vortex-ring like eddies that scale with the nozzle diameter in both the single and coaxial jets. The outward radial velocity associated with the leading edge of these vortical structures leads to radial spreading and mixing of the acetone-seeded single jet or annular jet fluid with the ambient. Small-scale motions near the leading edge of these vortical structures are simultaneously enhanced by the high-frequency component of the actuation waveform. In the coaxial jets, radial flow toward the jet centerline upstream of these vortical structures leads to advection of fluid from the annular (acetone-seeded in the PLIF investigations) flow toward the jet centerline and substantial mixing with the unseeded core flow. In the single jet, the mixed fluid fraction is actually lower with amplitude modulation than with unmodulated high-frequency forcing, indicating that the absence of forcing and small-scale motions during the inactive part of the duty cycle more than offsets the advantage of large-scale entrainment.

A spinning mode with $m = +1$ of the primary jets is introduced by azimuthal variation of the modulating waveform to the actuators. During a modulation cycle, the region of maximum axial velocity precesses in the clockwise direction. The radial distance of this region from the geometric centerline increases with downstream distance resulting in a helical structure. The regions of pure jet or annular fluid and the regions of intense mixing also precess around the geometric centerline at the modulation frequency, resulting in highly non-uniform mixing in the cross stream planes.

The present work has elucidated two primary effects of high-frequency forcing in the axial configuration (in the presence and absence of modulation). First, there is a substantial increase in small-scale motions as measured by rms velocity fluctuations within the primary jet mixing layer. The small scale motions are induced both by direct contact between the control jets and the primary flow and by transmission across the potential flow (ostensibly by pressure fluctuations) into the shear layer between the coaxial jets. The increase in small-scale motions is accompanied by an increase in mixing even in the absence of modulation and because the forcing input decays with streamwise distance, its effect is most pronounced within the first two flow diameters downstream of the jet exit plane. The present work has also shown that a coaxial flow configuration in which the velocity of the jet core is lower than that of the outer annular flow of the primary jet (i.e., wake-like flow), is substantially more receptive to the forcing than a jet-like configuration, resulting in increased mixing enhancement.

The second effect of high-frequency forcing in the axial configuration is the radial spreading of the primary jet flow toward the active actuators at the jet exit plane due to the entrainment induced by the actuators. Amplitude modulation of the actuation waveform results in flow transients that are associated with the onset and termination of the radial spreading (at the beginning and end of each modulation cycle). The radial motion leads to substantial modification of the jet column on scales that are commensurate with the streamwise wavelength of the modulation waveform. Furthermore, the present work has also shown that these flow transients that are characterized by the strong radial velocity oscillations near the jet exit plane lead to the formation of vortical structures near the downstream edge of these intermittent, time-periodic variations in the structure of the jet column. The formation of the large-scale structures in the single primary jet alters the entrainment of ambient fluid near the radial edges of the primary jet. The mixing parameter (mixed fluid fraction, γ_m) is a measure of the average fraction of mixed fluid [i.e., having acetone concentration (in this case) that is below the seeded concentration] and thus, in the case of the single primary jet, is a measure of the penetration of the jet mixing layer toward its centerline. Since the effect of the large-scale structures that are induced by the modulation is mostly limited to the radial edge of the primary jet, resulting enhancement in mixing in this outer region (where the acetone concentration is below the seeded concentration without enhancement) does not contribute to a change in γ_m.

The effect of amplitude modulated forcing on a coaxial jet where the core flow is faster than the annular flow (i.e., jet-like velocity ratio $U_i / U_o > 1$) is similar to the case of the single jet because the induced oscillations in radial velocity are limited to the radial edge of the primary jet and result in little mixing enhancement within its core. Amplitude modulation leads to a more significant increase in mixing when the velocity of the coaxial jet core is lower than in the annular flow (i.e., wake-like, $U_i / U_o < 1$) due to significant inward radial velocity throughout the jet cross section that follows the induced outward radial velocity at the beginning of the actuation cycle. The inward radial velocity develops at the outer radial edge of the primary jet as fluid is entrained into a low-pressure region that is formed by the outer radial motion at the beginning of the actuation cycle when the jet is diverging. As noted earlier, in wake-like coaxial jets the annular flow is inherently directed toward the centerline into the low-pressure region within the core of the inner jet even in the absence of forcing (Champagne & Wygnanski, 1971). This structure of the unforced base flow amplifies the inward radial velocity that is induced by amplitude modulation, resulting in inward radial velocity throughout almost the entire jet cross section. Mixing enhancement in the wake-like flows with amplitude modulation occurs primarily due to the advection of annular fluid to the jet centerline during this phase of the modulation cycle. The large-scale transport of annular fluid into the core of the coaxial jet results in more effective mixing enhancement in the wake-like flows than in the jet-like coaxial flow (or in the single jet).

While both the velocity data and the global (averaged) mixing data indicate that mixing is primarily enhanced near the exit plane (especially $x / D < 1$), the PLIF images of the forced flow show there is more mixed fluid downstream (e.g., $2 < x / D < 4$) in the forced flow than in the unforced flow. Furthermore, even though the velocity data indicate that compared to the unforced flow the effects of the forcing are more pronounced in the near field, PLIF images of the forced flow show larger concentrations of mixed fluid farther downstream. These results are consistent in that the mixed fluid concentration at a given downstream station includes the cumulative (history) effect of upstream mixing. Therefore, mixing enhancement in the near field of the forced flow leads to the presence of more mixed fluid at a given station downstream where the mixing rate in the unforced flow approaches the same rates as in the forced flow.

The present work has emphasized the need for closely-coupled measurements of the velocity and scalar fields. For example, the more than two-fold increase in entrainment with amplitude modulation in the single jet is not necessarily accompanied by mixing enhancement of the same magnitude due to the difference in radial locations where entrainment and mixing occur. Furthermore, the present work did not include an investigation of the sensitivity of the forced flow to either the placement of the actuators or to the level of forcing. Thus, with the understanding of the velocity field induced by the actuation and the mechanism for mixing enhancement obtained in this investigation, refinement of the forcing level should be obtained through quantitative measurements of the scalar field.

List of Publications

Non-refereed ~~Papers~~

Davis, S. A., Ritchie, D. B., Seitzman, J. M., and Glezer, A., "The Manipulation of Coaxial Jets using Synthetic Jet Actuators," Eighth European Turbulence Conference, Barcelona, Spain, June, 2000.

Davis, S. and Glezer, A. "Manipulation of Large- and Small-Scales in Coaxial Jets using Synthetic Jet Actuators," AIAA Paper 2000-0403, 38th Aerospace Sciences Meeting Conference and Exhibit, Reno, NV, January 2000.

Davis, S. and Glezer, A. "Manipulation of Large- and Small-Scales in Coaxial Jets using Synthetic Jet Actuators," AIAA Paper 2000-0403, 38th Aerospace Sciences Meeting Conference and Exhibit, Reno, NV, January 2000.

Participating scientific personnel

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Smith, B. L. & Glezer, A., "The Formation and Evolution of Synthetic Jets," *Phys. Fluids*, 10, 1998, pp. 2281-2297.

Davis, S. A. & Glezer, A., "Mixing Control of Fuel Jets Using Synthetic Jet Technology: Velocity Field Measurements," AIAA Paper 99-0447, 37th Aerospace Sciences Meeting, Reno, NV, 1999.

Ritchie, B. D. & Seitzman, J. M., "Acetone Mixing Control of Fuel Jets Using Synthetic Jet Technology: Scalar Field Measurements," AIAA Paper 99-0448 37th Aerospace Sciences Meeting, Reno, NV, 1999.

Nonlinear Robust and Adaptive Control for Combustion and Compression Systems

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Research Objectives

The ability of developing an integrated control-system design methodology for robust, high performance controllers satisfying multiple design criteria and real-world hardware constraints is imperative in light of the increasingly complex nature of variable-cycle gas turbine engines. The increasingly stringent performance requirements required for controlling such modern engineering systems necessitates a trade-off between control law complexity and control law robustness. Hence, one of the predominant considerations of modern multivariable control theory is to develop a control law design framework for combustion and propulsion systems that minimizes control law complexity subject to the achievement of a specified accuracy in the face of a specified level of modeling uncertainty. As part of this research program we proposed the development of a general hierarchical nonlinear robust and adaptive control framework that minimizes control law complexity subject to the achievement of control law robustness. In particular, we concentrated on hybrid control, impulsive dynamical systems, nonlinear switching control, robust control, and adaptive control for combustion and propulsion systems.

Description of Work Accomplished

Controls research by the Investigator Wassim M. Haddad has concentrated on nonlinear robust and adaptive control for combustion and propulsion systems [1–46]. The following are *some* of the research accomplishments that have been completed under this program.

Nonlinear Hybrid Dynamical Systems: Stability, Dissipativity, Feedback Interconnections, and Optimality

In this research [14,15,39,41] we developed Lyapunov and invariant set stability theorems for nonlinear impulsive dynamical systems. Furthermore, we generalized dissipativity theory to nonlinear dynamical systems with impulsive effects. Specifically, the classical concepts of system storage functions and supply rates are extended to impulsive dynamical systems providing a generalized hybrid system energy interpretation in terms of stored energy, dissipated energy over the continuous-time system dynamics, and dissipated energy over the resetting instants. Furthermore, extended Kalman-Yakubovich-Popov conditions in terms of the impulsive system dynamics characterizing dissipativeness in terms of system storage functions are derived. In addition, the framework is specialized to passive and nonexpansive impulsive systems to provide a generalization of the classical notions of passivity and nonexpansivity for nonlinear impulsive systems. Furthermore, we build on these results to develop general stability criteria for feedback interconnections of nonlinear impulsive systems. Finally, a unified framework for hybrid feedback optimal control involving a hybrid nonlinear-nonquadratic performance functional is developed. It is shown that the hybrid cost functional can be evaluated in closed-form as long as the cost functional considered is related in a specific way to an underlying Lyapunov function that guarantees asymptotic stability of the nonlinear closed-loop impulsive system. Furthermore, the Lyapunov function is shown to be a solution of a steady-state, hybrid Hamilton-Jacobi-

Bellman equation. These results were used to develop hybrid controllers for thermoacoustic combustion instabilities [42,43] (see also Section 2.2).

Active Control of Combustion Instabilities via Hybrid Controllers

In [14,15] a novel class of hybrid controllers, called resetting controllers, were proposed. The key idea of resetting control is to achieve enhanced energy dissipation between interconnected systems. Specifically, if a dissipative or lossless plant is at a high energy level, and a dissipative feedback controller at a low energy level is attached to it, then energy will generally tend to flow from the plant into the controller, decreasing the plant energy and increasing the controller energy. Of course, emulated energy, and not physical energy, is accumulated by the controller. Conversely, if the attached controller is at a high energy level and the plant is at a low energy level, then energy can flow from the controller to the plant, since a controller can generate real, physical energy to effect the required energy flow. Hence, if and when the controller states coincide with a high emulated energy level, then we can *reset* these states to remove the emulated energy so that the emulated energy is not returned to the plant. Since active energy flow resetting control for interconnected systems gives rise to discontinuous closed-loop motions, impulsive differential equations provides the mathematical foundation for analyzing resetting controllers. As discussed in Section 2.1, in [14,15] we developed a general framework for feedback systems possessing discontinuous motions by addressing stability, dissipativity, feedback interconnections, and optimality of nonlinear impulsive dynamical systems. The results in [14,15] apply to general nonlinear dynamical systems with abstract energy concepts for which a physical system energy interpretation is not necessary.

Engineering applications involving steam and gas turbines and jet and ramjet engines for power generation and propulsion technology involve combustion processes. Due to the inherent coupling between several intricate physical phenomena in these processes involving acoustics, thermodynamics, turbulence, and chemical reactions, the dynamic behavior of combustion systems is characterized by highly complex nonlinear models. The unstable dynamic coupling between heat release in combustion processes generated by reacting mixtures releasing chemical energy and unsteady motions in the combustor develop acoustic pressure and velocity oscillations which can severely impact operating conditions and system performance. These pressure oscillations, known as thermoacoustic instabilities, often lead to high vibration levels causing mechanical failures, high levels of acoustic noise, high burn rates, and even component melting. Utilizing a time-averaged combustion model for capturing thermoacoustic instabilities, in this research [42,43] we developed active energy flow resetting controllers to mitigate combustion induced pressure instabilities in combustion systems. The overall framework demonstrates that resetting controllers provide an extremely effective way for dissipating energy in combustion processes.

Hierarchical Nonlinear Control

Since advanced combustion/propulsion systems are inherently nonlinear with system nonlinearities arising from numerous sources, plant nonlinearities must be accounted for in the control-system design process. However, since combustion/ propulsion systems can exhibit multiple equilibria, limit cycles, bifurcations, jump resonance phenomena, and chaos, general combustion/propulsion system stabilization is notoriously hard and remains an open problem. Control system designers have usually resorted to Lyapunov methods in order to obtain stabilizing controllers for nonlinear systems. In particular, for smooth feedback, Lyapunov-based methods were inspired by Jurdjevic and Quinn who give sufficient conditions for smooth stabilization based on the ability of constructing a Lyapunov function for the closed-loop system. Unfortunately, however, there does not exist a unified procedure for finding a control Lyapunov function candidate that will stabilize the closed-loop system for general nonlinear systems.

If the operating range of the control system is small and if the system nonlinearities are smooth, then the control system can be locally approximated by a linearized system about a given operating condition and linear multivariable control theory can be used to maintain local stability and performance. However, in high performance aerospace engineering applications such as variable-cycle gas turbine aeroengines, the locally approximated linearized system does not cover the operating range of the system dynamics. In this case, gain scheduled controllers can be designed over several fixed operating points covering the system operating range and controller gains interpolated over this range. However, due to approximation linearization errors and neglected operating point transitions, the resulting gain scheduled system does not have any guarantees of performance or stability. Even though stability properties of gain scheduled controllers are analyzed in the literature and stability guarantees are provided for plant output scheduling, a *design* framework for gain scheduling control guaranteeing system stability over an operating range of the nonlinear plant dynamics has not been addressed in the literature.

In an attempt to develop a design framework for gain scheduling control, linear parameter-varying system theory has been developed. Since gain scheduling control involves a linear parameter-dependent plant, linear parameter-varying methods for gain scheduling seem natural. However, even though this is indeed the case for linear dynamical systems involving exogenous parameters, this is not the case for nonlinear dynamical systems. This is due to the fact that a nonlinear system cannot be represented as a true linear parameter-varying system since the varying system parameters are endogenous, that is, functions of the system state. Hence, stability and performance guarantees of linear parameter-varying systems do *not* extend to the nonlinear system. Of course, in the case where the magnitude and rate of the endogenous parameters are constrained such that the linear parameter-varying system *hopefully* behaves closely to the actual nonlinear system, then *a posteriori* stable controllers can be designed. However, in the case of unexpectedly large amplitude uncertain exogenous disturbances and/or system parametric uncertainty, *a priori* assumptions on magnitude and rate constraints on endogenous parameters are unverifiable.

In this research [10,13,17,31,34,35,40,46] a nonlinear control design framework predicated on a stability-based switching controller architecture parameterized over a set of system equilibria is developed. Specifically, using *equilibria-dependent Lyapunov functions* or, instantaneous (with respect to a given parameterized equilibrium) Lyapunov functions, a hierarchical nonlinear control strategy is developed that stabilizes a given nonlinear system by stabilizing a collection of nonlinear controlled subsystems. Each subcontroller can be nonlinear and thus local set point designs can be nonlinear. Furthermore, for each parameterized equilibrium the collection of subcontrollers provide guaranteed domains of attraction with nonempty intersections that cover the region of operation of the nonlinear system in the state space. A switching nonlinear controller architecture is developed based on a *generalized* lower semicontinuous Lyapunov function obtained by minimizing a potential function, associated with each domain of attraction, over a given switching set induced by the parameterized system equilibria (see Figure 1). The switching set specifies the subcontroller to be activated at the point of switching, which occurs within the intersections of the domains of attraction. The hierarchical switching nonlinear controller guarantees that the generalized Lyapunov function is nonincreasing along the closed-loop system trajectories with strictly decreasing values at the switching points, establishing asymptotic stability. In the case where one of the parameterized system equilibrium points is globally asymptotically stable, the proposed nonlinear stabilization framework guarantees global asymptotic stability of any given system equilibrium on the parameterized system equilibrium branch. Furthermore, since the proposed switching nonlinear control strategy is predicted on a generalized Lyapunov function framework with strictly decreasing values at the switching points, the possibility of a sliding mode is precluded. Hence, the proposed nonlinear stabilization framework avoids the undesirable effects of high-speed switching onto an invariant sliding manifold which is one of the main limitations of variable structure controllers. This hierarchical controller framework was used in [3,11,12] for controlling rotating stall and surge in axial and centrifugal flow compressors.

Globally Stabilizing Controllers for Multi-Mode Axial Flow Compressor Models via Equilibria-Dependent Lyapunov Functions

In this research [3,11,22,24,26,46] we developed a self-contained first principles derivation of a multi-mode model for rotating stall and surge in axial flow compression systems that is accessible to control-system designers requiring state space models for modern nonlinear control design. Specifically, the formulation is based on a generalized multi-mode expansion of the disturbance velocity potential in the flow field which accounts for the coupling between higher-order system harmonics and the pressure rise and mean flow through the compressor. Using the multi-mode state space model we show that the globally stabilizing backstepping controller developed by Kokotovic and co-workers predicated on the one-mode Moore-Greitzer model drives the compression system to a stalled condition in the case where two-modes are included in the model. This clearly indicates that the higher-order disturbance velocity potential harmonics strongly interact with the first harmonic during stall inception and must be accounted for in the control design process to achieve control performance objectives.

Using Lyapunov stability theory, a novel nonlinear globally stabilizing control law for the multi-mode axial flow compressor models based on equilibria-dependent Lyapunov functions with converging domains of attraction is developed [46]. The locus of equilibrium points on which the equilibria-dependent, or instantaneous, Lyapunov functions are predicated are characterized by the axisymmetric equilibria of the compression system. The proposed nonlinear controller guarantees global stability for an arbitrary number of modes in the compression system.

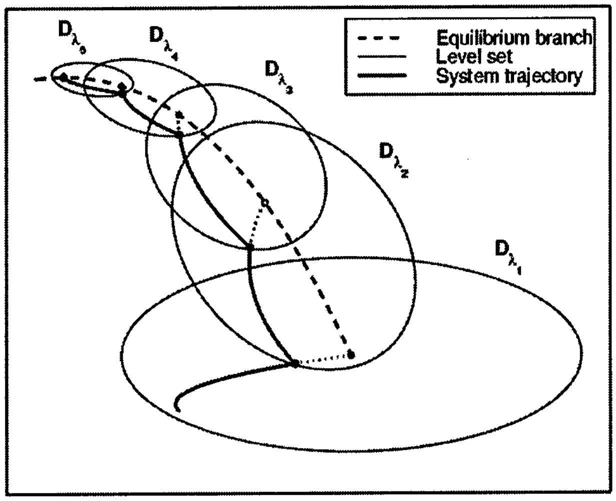

Figure 1. Stability-based switching control strategy

Globally Stabilizing Control for Centrifugal Compressors

While the literature on modeling and control of compression systems predominantly focuses on axial flow compression systems, the research literature on centrifugal flow compression systems is rather limited in comparison. In contrast to axial flow compression systems involving the aerodynamic instabilities of rotating stall and surge, surge and deep surge is the predominant aerodynamic instability arising in centrifugal compression systems. Surge is a one-dimensional axisymmetric global compression system oscillation which involves radial flow oscillations and in some case even radial flow reversal (deep surge) which can damage engine components.

In this research [12,32,38,46] we addressed the problem of nonlinear stabilization for centrifugal compression systems. First, we developed a three-state lumped parameter model for surge in centrifugal flow compression systems that are accessible to control-system designers requiring state space models for modern nonlinear control. Specifically, pressure and mass flow compression system dynamics are developed using principles of conservation of mass and momentum. Furthermore, in order to account for the influence of speed transients on the compression surge dynamics, turbocharger spool dynamics are also considered.

Next, using a Lyapunov-based framework, we developed a globally stabilizing control law for the lumped parameter centrifugal compressor surge model. In particular, using the backstepping control framework, a control Lyapunov function for the closed-loop system is constructed leading to a nonlinear control architecture involving throttle and compressor torque regulation. The proposed nonlinear controller is applied to the developed centrifugal compressor surge model with spool dynamics. Figure 2 shows the pressure-flow (ψ–ϕ) phase portrait of the state trajectories when the controlled and uncontrolled compression system is taken from an operating speed of 20,000 rpm to 25,000 rpm. Finally, actuator amplitude and rate saturation constraints are also addressed [12,46].

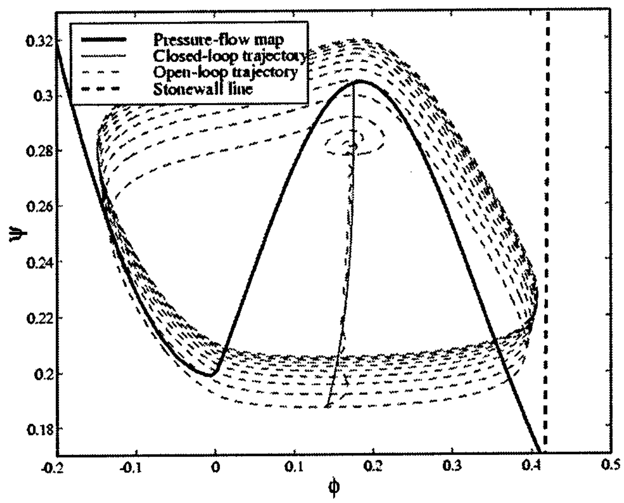

Figure 2. Controlled and uncontrolled phase portrait of pressure-flow state trajectories from 20,000 rpm to 25,000 rpm

Inverse Optimal Adaptive Control for Nonlinear Systems with Exogenous Disturbances

A Lyapunov-based optimal adaptive control-system design problem for nonlinear uncertain systems with exogenous L_2 disturbances is considered [8,30]. Specifically, an inverse optimal adaptive nonlinear control framework is developed to explicitly characterize globally stabilizing disturbance rejection adaptive controllers that minimize a nonlinear-nonquadratic performance functional for nonlinear cascade and block cascade systems with parametric uncertainty. It is shown that the adaptive control Lyapunov function guaranteeing closed-loop stability is a solution to the Hamilton-Jacobi-Isaacs equation for the controlled system and thus guarantees both optimality and robust stability. Additionally, the adaptive control Lyapunov function is dissipative with respect to a weighted input-output energy supply rate guaranteeing closed-loop disturbance rejection. For special integrand structures of the performance functionals considered, the proposed adaptive controllers additionally guarantee robustness to multiplicative input uncertainty. In the case of linear-quadratic control it is shown that the operations of parameter estimation and controller design are coupled illustrating the breakdown of the certainty equivalence principle for the optimal adaptive control problem. Finally, the proposed framework is used to design adaptive controllers for jet engine compression systems with uncertain compressor performance pressure-flow maps.

Nonlinear Robust Disturbance Rejection Controllers for Rotating Stall and Surge in Axial Flow Compressors

The desire for developing an integrated control system-design methodology for advanced propulsion systems has led to significant activity in modeling and control of flow compression systems in recent years. However, unavoidable discrepancies between compression system models and real-world compression systems can result in degradation of control-system performance including instability. In particular, jet engine compression systems with uncertain performance pressure-flow characteristic maps can severely limit jet engine compression system performance by inducing the compressor aerodynamic instabilities of rotating stall and surge. Rotating stall is an inherently two-dimensional local compression system oscillation which is characterized by regions of flow that rotate at a fraction of the compressor rotor speed while surge is a one-dimensional axisymmetric global compression system oscillation which involves axial flow oscillations and in some cases even axial flow reversal which can damage engine components and cause flameout to occur.

In this research [4,27] we developed globally stabilizing robust/disturbance rejection controllers for rotating stall and surge in axial flow compressors with uncertain compressor performance pressure-flow characteristic maps. Specifically, using the nonlinear-nonquadratic disturbance rejection optimal control framework for systems with bounded energy (square-integrable) L_2 disturbances developed in [1] and the nonlinear-nonquadratic robust optimal control framework for systems with nonlinear parametric uncertainty developed in [9], a *family* of globally robustly stabilizing controllers for jet engine compression systems is developed. The proposed controllers are compared with the locally stabilizing bifurcation-based controllers of Abed and Nett and the recursive backstepping controllers of Kokotovic.

Adaptive Control for Thermoacoustic Combustion Instabilities

High performance aeroengine afterburners and ramjets often experience combustion instabilities at some operating condition. Combustion in these high energy density engines is highly susceptible to flow disturbances, resulting in fluctuations to the instantaneous rate of heat release in the combustor. This unsteady combustion provides an acoustic source resulting in self-excited oscillations. In particular, unsteady combustion generates acoustic pressure and velocity oscillations which in turn perturb the combustion even further. These pressure oscillations, known as thermoacoustic instabilities, often lead to high vibration levels causing mechanical failures, high levels of acoustic noise, high burn rates, and even component melting. Hence, the need for active control to mitigate combustion induced pressure instabilities is severe.

Due to the intricate complex physical phenomena in combustion processes involving acoustics, thermodynamics, fluid mechanics, and chemical kinetics, finite dimensional linear or nonlinear models are unavoidably inaccurate. Basic system data such as damping, frequency, and mode shapes are often poorly known. Furthermore, approximations of pressure and velocity fluctuations involving time-averaging in the governing system equations result in further system uncertainty that manifests itself as highly structured constant real parametric uncertainty in modal frequencies and damping. Thus for pressure oscillation suppression in combustion processes, system modeling uncertainty necessitates the need for nonlinear adaptive control.

In this research [45] we developed a Lyapunov-based direct adaptive control framework to suppress the effects of thermoacoustic instabilities in combustion processes. The overall framework demonstrates that the proposed adaptive controllers provide considerable robustness in suppressing thermoacoustic combustion instabilities in the presence of parametric uncertainties in the model.

State Space Modeling and Robust Reduced-Order Control of Combustion Instabilities

Thermoacoustic instabilities in combustion processes can have adverse effects on jet engine propulsion system performance. In this research [7,23,25] we formulated the problem of active control of combustion instabilities in a form that lends itself to the application of robust feedback control design. Specifically, a self-contained first principles derivation of the dynamic governing equations for combustion instabilities that is accessible to control-system designers requiring state space models for modern robust feedback control design is developed. Using the uncertain state-space system model the parameter-dependent Lyapunov function framework of Haddad and Bernstein for robust fixed-order controller design is used to design high performance reduced-order robust controllers for suppressing thermoacoustic oscillations in combustion chambers.

Research Personnel Support

Faculty

Wassim M. Haddad, Professor

Graduate Students

Alexander Leonessa, received his Ph. D. under this program in 1999.

Joseph R. Corrado, received his Ph. D. under this program in 2000.

Natаsa A. Kablar, received her M. S. under this program in 2001.

Tomohisa Hayakawa, a Ph. D. student.

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Combustion Instability Control with Neural Network Chip

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Introduction

A hardware neural network chip has successfully been used to control a simulated combustion instability. This chip uses a single layer neural network with 8 inputs. We have performed many simulations that show that neural network models of this chip will control a variety of combustion instability models, this is the first result showing that actual neural network hardware will control a simulated combustion instability. We are now working towards controlling a real combustion instability.

Results

The test setup is shown as in Figure . The computer runs a program simulating unstable limit-cycle combustion differential equation models [Neumeier 97]. The chip shown in this figure is a mixed signal neural network chip fabricated for this project. The computer simulation and neural network chip are connected via two data acquisition cards, and together form a closed loop. The engine output is tap-delayed and sent to the input of the chip through the analog output card (AT-AO-10). These inputs are forward propagated through the neural network chip, and generate an output. The weights of the neural network determine its characteristics and thus the control implemented. They are adjusted by the random weight change algorithm [Hirotsu 93] which seeks to reduce the error between the desired output and the actual output. In this case, the error is determined by the magnitude of the engine output. Since we want to stabilize the engine, we want the oscillation magnitude to be zero. The chip output is a current. It is converted to a voltage, and read in to the computer by the analog input card (AT-MIO-16E).

Typical experimental results showing the chip controlling the simulated unstable combustion process from a cold start (neural net weights are all zero) are shown in Figure 2 and Figure 3. The engine instability was simulated using nonlinear differential equations that we solve by a Runge-Kuta method with a time step of 0.125 millisecond.

The results show that the chip can stabilize the instabilities. When the chip has learned, the engine pressure is limited to a small amplitude. But it also shows that after a while, the engine output slowly grows again. This may be due to degradation of the chip weights with time, or noise or upsets in the test setup erasing the weights. The two results we present here are from the same program, and the same chip biased with the same voltages, run a two different times.

Future Directions

We are currently setting up to test the neural network chips ability to control a real (not simulated) process. We have a forced air setup that produces sustained acoustic oscillations and will attempt to suppress them with the chip. If that succeeds we then will make the chip available to the combustion group for experiments on an actual combustion process.

In addition we are fabricating an updated version of the chip with 7 times more weights (720) and 3 times as many inputs (30). We hope this new chip will be able to perform even better than the current one.

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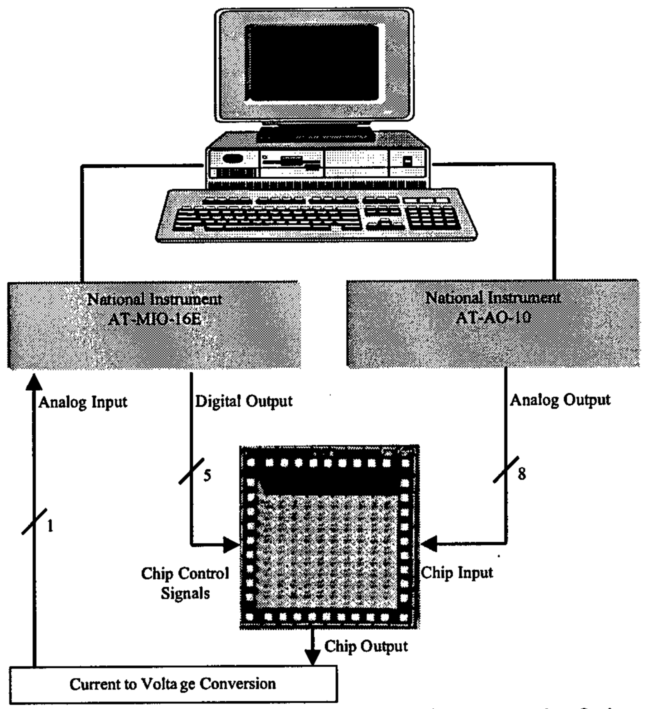

Figure 1. Experimental test setup for neural net chip control of simulated combustion process.

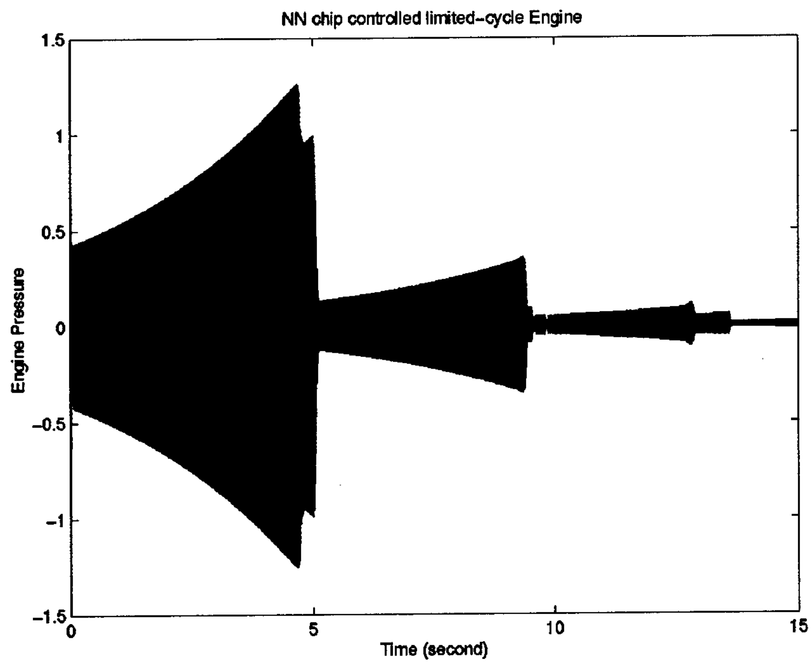

Figure 2. Typical result of the neural net chip controlling simulated combustion.

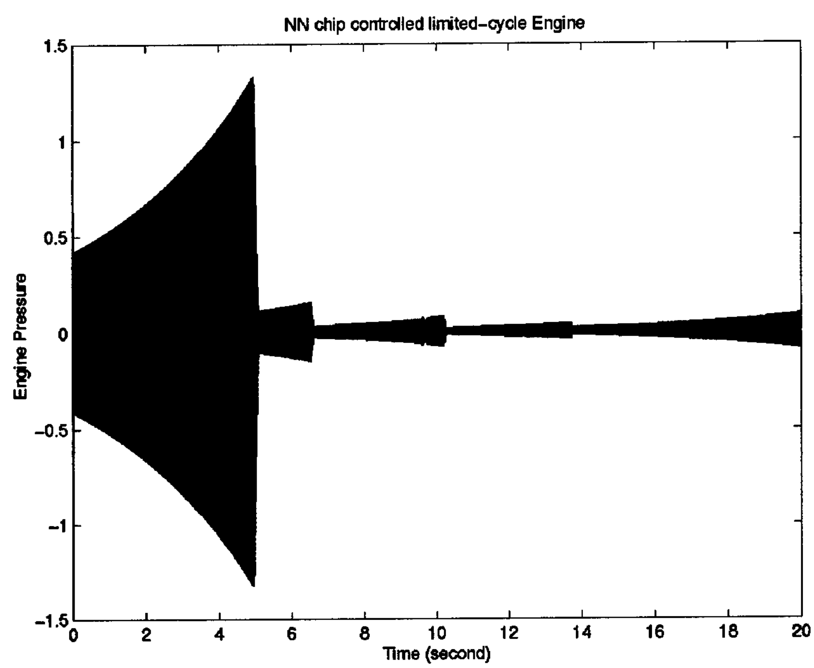

Figure 3. Typical result of the neural net chip controlling simulated combustion.

Development of LES for Single and Two Phase Combustor Flows

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Problem Statement

A new LES methodology to be developed to simulate turbulent single- and two-phase combustion.

Summary of Results

A new simulation approach based on LES has been developed under this MITE program. The LES approach solves non-premixed and premixed single-phase and also spray combustion within a single formulation. The unique feature of this model is its ability to capture the interaction between turbulent fluctuations and scalar fields using an innovative subgrid model. In this model, the reaction-diffusion processes are solved within the LES grid using a localized direct simulation and then its is coupled to the LES filtered equations for mass, momentum and energy which are solved on the LES grid. The key advantages of this approach is that reaction kinetics is closed without requiring any models, the molecular diffusion processes are included within the subgrid model and the effect of small-scale turbulent mixing on the scalar field is simulated using a stirring process. For spray combustion, the Eulerian gas phase field is coupled to the Lagrangian particle phase model to simulate droplet motion. The subgrid model is also modified to account for the presence of the droplets.

Application of this LES approach to very high Re premixed and spray combustion in both laboratory scale and full-scale devices has been carried out and the results validated against experimental data, wherever available. The results have been reported in numerous publications that are listed below.

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Personnel Working on Project

Post Doctoral Fellows

Won-Wook Kim, 1998-1999

Ph.D. Students

Kalyan Chakravarty, received his Ph.D. in 2000

On Stochastic Subgrid Modeling for Large-Eddy Simulations of Premixed Flames

Sreekant Pannala, received his Ph.D. in 2000

On Large-Eddy Simulations of Reacting Two-Phase Flow

Vaidyanathan Sankaran, a Ph.D. student still working on his thesis; started in 1997 and expected to complete his studies in 2002.

CFD of Unsteady Compressor Flows

L. N. Sankar

School of Aerospace Engineering

Task Objectives

(a) Develop first-principles based method for understanding the physics behind the flow instabilities such as rotating stall and surge that may arise in modern compressors,

(b) Develop active control strategies for eliminating and mitigating these instabilities, and

(c) Develop lower order models of the flow phenomena for use in control theory and modeling.

Task Accomplishments

A state-of-the-art, spatially high-order, 3-D flow solution methodology was developed for modeling unsteady flow within axial and centrifugal compressors. Novel non-reflective boundary conditions were developed for the compressor outflow, which allowed pressure waves to leave the downstream boundary into a plenum chamber without false reflections. The methodology was validated against experiments for a number of configurations such as the NASA Glenn Low Speed Centrifugal Compressor, DLR 4:1 high speed centrifugal compressor, and the NASA Glenn axial compressor Rotor 67. The methodologies were able to predict the compressor performance map, as well as the pressure field over the blade surfaces with sufficient accuracy. The results of these validation efforts were published in the Ph. D. thesis dissertations of Saeid Niazi, and Alex Stein, and numerous publications. Electronic versions of these publications may be found at http://www.ae.gatech.edu/~lsankar/MURI .

The development of rotating stall and surge within the centrifugal compressor was investigated. It was demonstrated that bleeding downstream of the compressor was an effective way of eliminating surge. It was also demonstrated that a high speed jet (steady, or pulsed) may also be used upstream of the compressor face. Parametric studies were done to determine the optimum mass flow rates and frequencies for elimination of surge in the DLR 4:1 compressor. It was shown that the jet yaw angle played a critical role in restoring flow stability.

Actively control of rotating stall in axial compressors was studied. It was found that a rule based control, where bleeding is triggered whenever the plenum pressure exceeds predetermined ranges, is quite effective and can reduce the amount of bleeding needed to maintain a stable operation.

Two dimensional versions of the compressor solvers, and a reduced order model were also developed in collaboration with Dr. J. V. R. Prasad and his doctoral student Dr. Carlos Rivera.

List of Publications

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Manipulating Pattern Factor Using Synthetic Jet Actuators

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STATEMENT OF PROBLEM

The temperature distribution at the exit of a gas turbine combustor, or pattern factor, is one of the key parameters in evaluating the performance of this type of engine. Good mixing between hot combustion products and cooling air at the exit to the combustor is essential for removing the hot spots in the temperature profile at the entrance to the turbine. There are many passive and active methods to improve dilution mixing at the exit of turbine engine combustor. Passive control techniques generally involve modification of the geometry of the combustor and the path through which the cold air is introduced into the dilution zone and is often only effective at design condition. In some active control techniques, pulsed or non-pulsed air jets are used to achieve improved mixing in the dilution zone. However, all these techniques require introducing significant amount of air from the compressor directly to the dilution zone.

Since the turbine blades of future engines will be able to withstand much higher temperatures but not adiabatic flame temperature, less cooling air will be available to control the mixing process in the dilution zone of the combustor. The present study, therefore, investigates the possibility of using zero mass flow synthetic jets to optimize the pattern factor without sacrificing the compressor performance and without adding too much weight to the turbine engine.

Results described elsewhere in this report as well those of previous experimental and computational studies have demonstrated that synthetic jets can be used for flow control, lift generation, vectoring larger jets and mixing enhancement between co-flowing jets [2,3,4,5,6]. In this part of the study we have shown that synthetic jets can also enhance mixing when injected normally into flows with stratified temperature profiles.

RESULTS OF STUDY

Experimental Methods

The experimental setup is shown in Fig. 1. The combustor consists of a rectangular chamber (450mm x 92mm x 75mm) with provisions for optical and probe access for flow or mixing visualization and velocity and temperature measurements. Cold shop air and hot combustion products from a premixed methane burner are introduced in parallel streams into the chamber. Synthetic jets enter through an orifice plate located at 145 mm downstream of the combustor entrance in the floor of the chamber. The jets are generated by a piston underneath the orifice plate moving up and down in a cylinder. This action pulls in air from the region above the floor of the chamber and then pushes it out in a jet normal to the orifice. In the present study, orifice plates with four holes of diameter 2.38 mm or with a single slot measured 1.6mm in width and 11.2mm in length were used. The hole pattern can be aligned stream-wise or crosswise to the main flow.

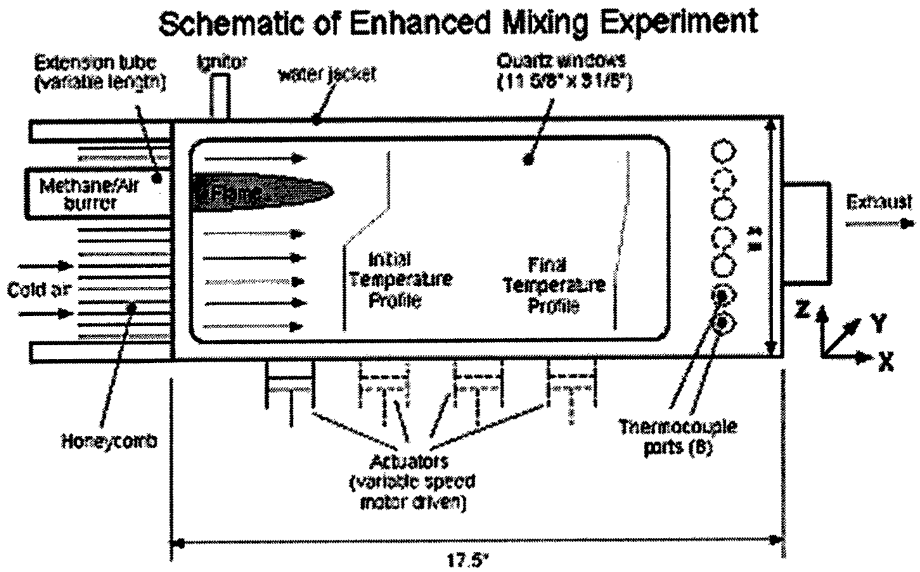


Figure 1. A Schematic of Experiment Set Up

Velocities in the pulsed jets could be varied independently of frequency and vice versa, using a jet bleed ring located under the actuator plate, see Fig. 2. This allowed extra air to be bled from the actuator without entering the chamber. The inner diameter of the ring is equal to that of the actuator chamber. There are eight holes in the sidewall, each of the same diameter as the holes in the 4-hole actuator plate. Each of the eight holes in the bleed ring can be sealed with a screw. By opening different numbers of holes we can vary the amount of air that issues through the actuator orifice for a given actuator frequency. Since the actuator now has holes open to the surroundings as well as to the combustion chamber, it can no longer be guaranteed that it is truly zero net-mass-flux. However, because of the small amount of fluid involved and since most of the air aspired comes from close to the floor of the chamber any net flux effect is expected to be small.

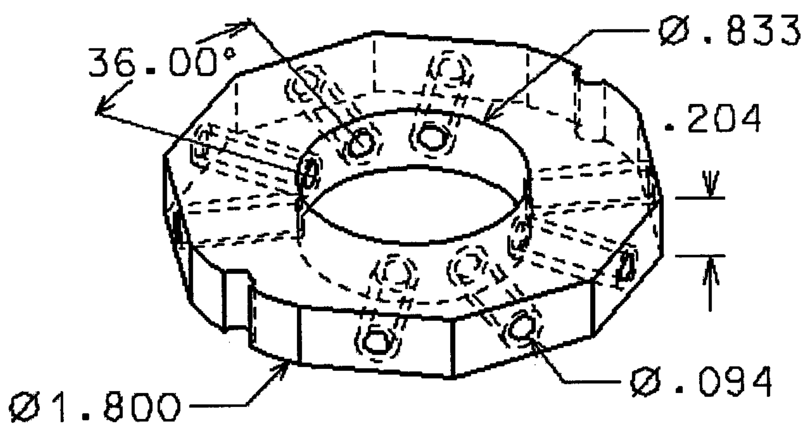


Figure 2. Pulsed Jet Bleed Ring

Temperatures were measured using a twelve K-type thermocouple rake that can be moved laterally 380-mm downstream of the test chamber entrance. This provided a complete 2-D temperature profile in a vertical plane across the test chamber. Pitot probes and hot film anemometers were used to measure flow velocities. Flow fields and mixing patterns were visualized using high speed shadowgraphy and Mie scattering, respectively. In the former a standard Schlieren set up was used. In the latter laser sheets were traversed through the test section vertically along and normal to the axis of the combustor as well parallel to the chamber flow. Seeding in the form of smoke was introduced into the cold flow, the hot flow or in the form of streak lines. In both cases the flow was visualized using a high resolution CCD camera.

Data Analysis

In order to be able to quantify the effect of the actuators on the degree of mixing and, thus, on the uniformity of the temperature in the exit plane, a parameter called "the fractional improvement", ξ, was introduced. This parameter is based on an entropy method first introduced by Everson et al.[7] to evaluate the degree of mixing between fluids with different concentrations of tracer. It was extended here to measure the degree of mixing between fluids with different temperatures. The underlying concept is that entropy increases as mixing improves and, therefore, as the temperature profile becomes more uniform.

The following assumptions were made to quantify the uniformity of temperature in the exit plane:

The thermodynamic properties (R, Cp) of the combustion products and air are the same.

The combustion products and air behave as thermally and calorically perfect gases.

For every measured temperature profile, with or without actuation, one can identify a fully mixed, hypothetical state characterized by a uniform temperature T_{final}. This state is reached from the current temperature profile by an adiabatic mixing process. Incidentally, this is the "ideal state" that the mixing process aims to achieve.

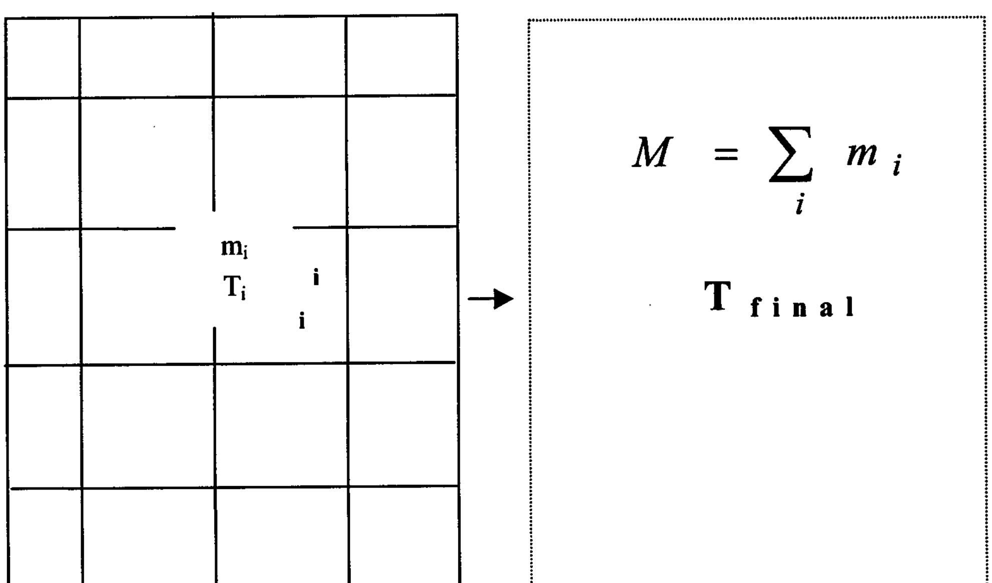


Figure 3. Calculation of fractional improvement for temperature uniformity

As shown in Fig. 3, the exit plane of the combustor, where the temperature distribution is measured by thermocouples, is divided by a grid into small elements, unit thickness, such that the thermodynamic properties in each element can be considered constant. If the element with temperature Ti has a volume ΔVi the mass of gas in this element is given by

$$m_i = p\Delta V_i /(RT_i) \qquad (1)$$

where p is the atmosphere pressure and R is the ideal gas constant per unit gas.

The total mass of the gas in the slice of unit thickness exit plane is

$$M = \sum_i m_i = \frac{p}{R}\sum_i \Delta V_i / T_i \qquad (2)$$

Conservation of energy for an adiabatic mixing process can be written as

$$h_0 = \sum_i m_i c_p (T_i - T_{ref}) = Mc_p (T_{final} - T_{ref}) \qquad (3)$$

where h_0 is the stagnation enthalpy and T_{final} and T_{ref} are the final and a reference temperature, respectively.

Equation (2) and (3) can be combined to give

$$T_{final} = \frac{V}{\sum_i \frac{\Delta V_i}{T_i}} \qquad (4)$$

From the definition of entropy, s, it can be shown that

$$ds = c_p \frac{dT}{T}$$

The total entropy increase between the measured temperature distribution in the combustor exit plane and the "ideal" fully mixed state of T_{final} is then given by:

$$\Delta S = \sum_i \Delta S_i = \sum_i m_i c_p \int_{T_i}^{T_{final}} \frac{dT}{T}$$

which can be normalized to a specific entropy change by

$$\Delta s = \frac{\Delta S}{M}$$

Each temperature distribution, therefore, has a value of Δs associated with it. In order to compare temperature uniformity without and with actuation let Δs_0 and Δs be the entropy changes between the measured and "ideal", the fully mixed state, for the cases without and with actuation. "The fractional improvement" is then defined as

$$\xi = 1 - \frac{\Delta s}{\Delta s_0}$$

Clearly, without actuation, ξ=0, while if actuation caused the temperature distribution to become totally uniform ξ=1. For more realistic situations ξ will fall between 0 and 1, whereby the bigger ξ, the larger the improvement due to actuation.

A similar scheme was developed to quantify the enhancement of mixing between the hot and cold flows by the actuators as recorded by planar Mie scattering.

Experimental Results and Discussion

Effect of Actuation on Temperature Distribution in the Exit Plane

The effect of the zero mass flow actuators on the temperature distribution in the exit plane of the combustor was measured using a 12 thermocouple rake traversed across the exit plane in 4 mm steps. These temperatures were measured downstream of the synthetic jets at x/d=80 where x is the distance downstream of the actuators and d is the diameter of the synthetic jet orifice (=2.38mm).

Preliminary tests showed that the action of the zero mass flow actuators very significantly enhanced mixing. In a more detailed study the effects of jet velocity were differentiated from those of jet frequency by using the bleed ring described earlier to vary these two parameters independently. Figures 4 and 5 show the effects of these two parameters by plotting the fractional improvement in temperature uniformity vs. level of actuation, as described by the ratio peak jet to mean main flow velocities. (Details of these velocity measurements are given in the next sub-section.) Also included are images of 2-D temperature profiles for selected conditions, which not only give a more visual interpretation of the temperature gradients in the vertical direction but also illustrate the uniformity of temperature in the lateral direction.

Effect of Frequency on Temperature Uniformity

Experimental results for these tests are summarized in Fig. 4. Four different jet velocities were chosen. Each was obtained by combining the opening of different numbers of holes in the bleed ring with various driving frequencies. Clearly ξ is hardly effected by changes in frequency for any given jet velocity. This means that the frequency does not seem to play an important role in enhancing mixing, at least within a frequency range from 3 to 140Hz.

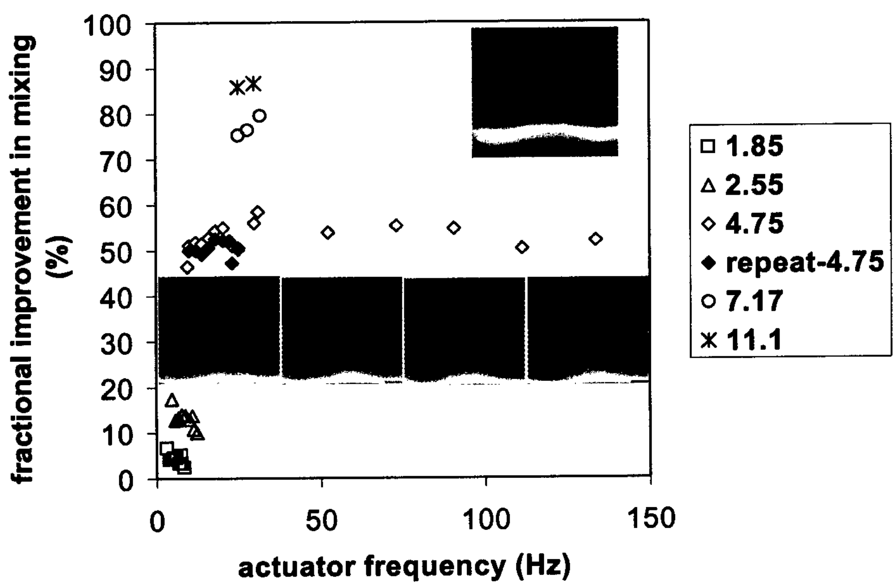


Figure 4. Frequency Effect on Fractional Improvement in Mixing

Effect of Velocity/Momentum Ratio on Temperature Uniformity

Previous studies of jets in cross flows have shown that the momentum ratio between any jets and a cross flow is an important factor in determining the flow field. Similar observations were made for synthetic jets in this study.

Since it has been shown that the effect of the actuator is independent of frequency, the effect of jet velocities on mixing can be determined by comparing the effect of jets with different velocities even if they were produced by operating the actuator at different frequencies. Peak jet velocities ranging from around 2m/s to 30m/s were investigated. Figure 5 summarizes the results in the form of a plot of ξ vs. velocity ratio. Data at different frequencies are included, as are multiple points at selected velocity ratios to show repeatability. Finally, selected temperature profiles are shown for some typical velocity.

The effect of the synthetic jets is not noticeable until Upj/Uc≈2. After that ξ increases steeply as the velocity ratio increases, from 5% at Upj/Uc≈2 to 80% at Upj/Uc≈8. Beyond that value the curve levels off. This indicates that there is an upper limit to the ability of the synthetic jets to enhance the mixing, beyond which the improvement is negligible. The temperature profiles in Fig. 5 indicate that the temperature is already quite uniform when $\xi \approx 80\%$, i.e., in the level-off region.

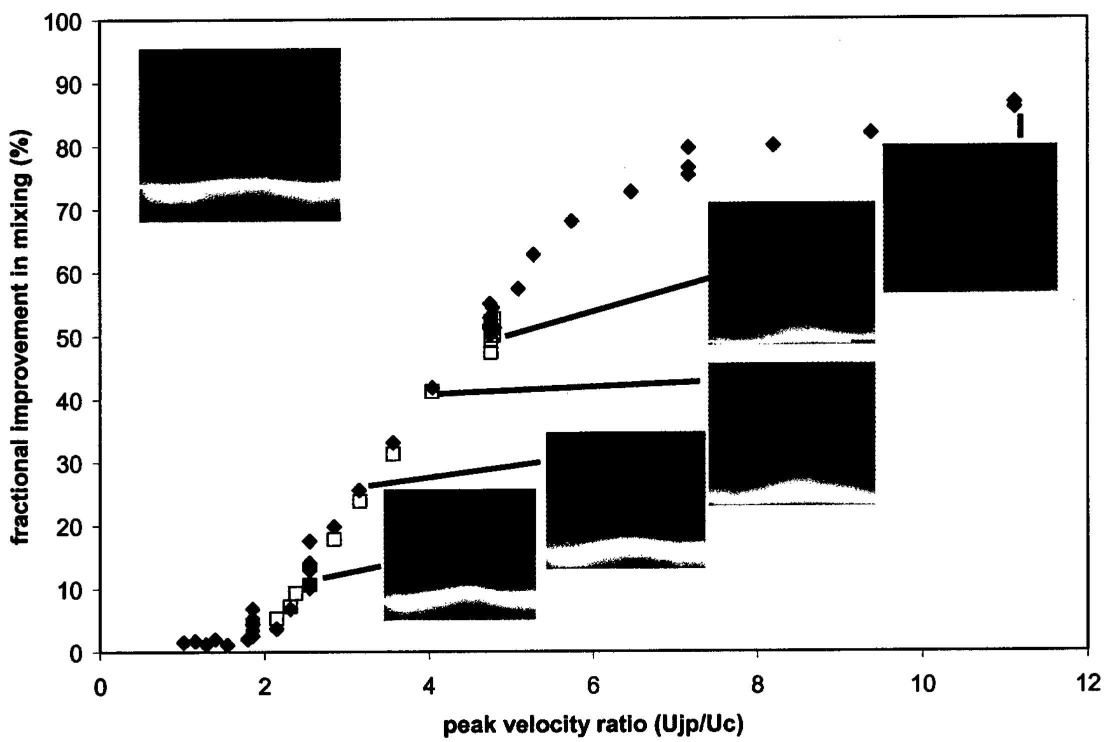


Figure 5. Velocity Ratio Effect on Fractional Improvement in Mixing

Similar tests were carried out for different equivalence ratios in the premixed burner providing the hot flow. This changed the temperature and, therefore, density differences between the hot and cold flows. The results showed that the extent to which synthetic jets enhance temperature uniformity depends more on the degree of actuation than the temperature difference between the different parts of the streams. In other words, the momentum ratio between the synthetic jet and cross flow, rather than the density ratio between hot and cold streams is the critical parameter.

Effects of Configuration and Orientation of Actuator

In these tests two types of actuator orifice plates were used. One contains a row of four 2.38mm diameter holes on 4mm centers, while the other has 1.6mm wide slot, which has the same area as the four holes. The four holes and slot were oriented normal to or parallel with the main flow. Different actuator shapes and orientations showed somewhat different effects on the temperature distribution for the same degree of actuation as characterized by the peak jet velocity. Multiple circular jets appear more effective than slots of equivalent area. In addition, the 4-circular jets placed normal to the flow are more efficient than if placed in the streamwise direction. However, all these differences were relatively small.

Velocity Measurements in Synthetic Jets

To identify the mechanism responsible for improved mixing by synthetic jets, it is necessary to understand the flow field generated by the interaction between the synthetic jets and, the cross-flow.

At first, the velocity field of an individual synthetic jet was measured in the absence of crossflow. As expected, higher actuation levels result in higher jet velocities. Therefore, vertical peak velocities during the cycle measured with hot wire at 2mm above the center of the orifice were used to characterize the actuation strength. Similar to a steady jet, the centerline velocity initially decreases slowly, then much more rapidly, and finally again more gradually. However, the rate of the velocity decay is much faster than that of a traditional jet. This may be caused by the unsteady nature of the synthetic.

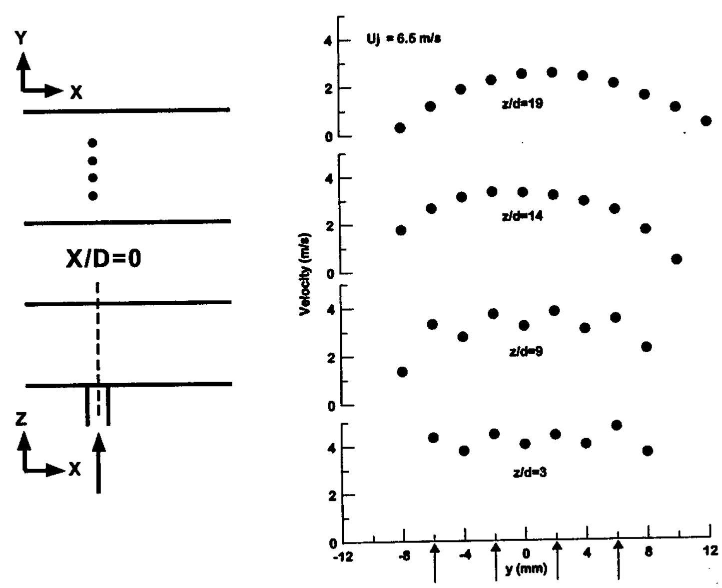


Figure 6. Flow Interactions between Synthetic Jets

The flow field resulting from interaction between the synthetic jets was measured and plotted as a function of vertical distance above the orifice in Fig. 6. Close to the orifice exit (z/d<10), contributions of the individual jets can be seen as distinct peaks in the combined flow. At z/d>14, the jets have completely merged and the resulting velocity profile is similar to that of a single jet.

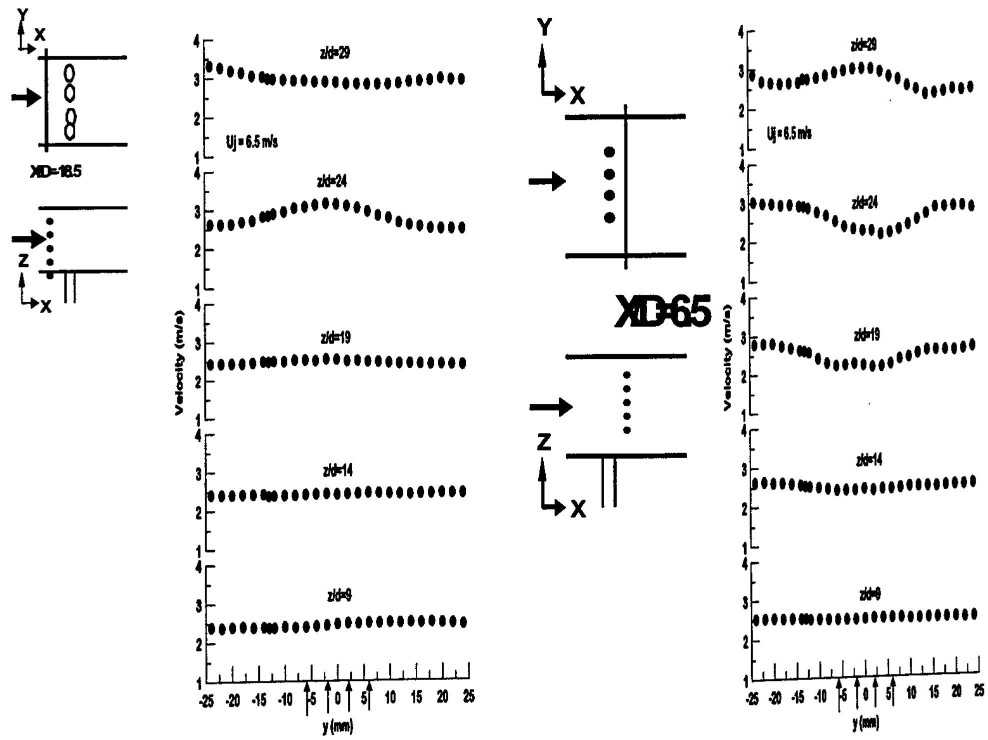


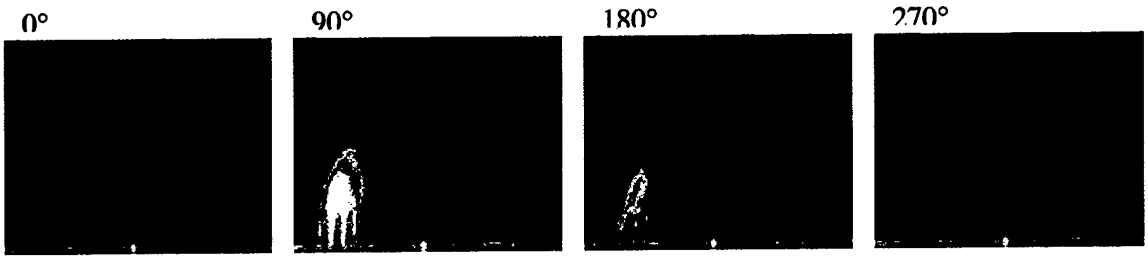
Figure 7. Crossflow Velocity Profiles

To determine the effect of the synthetic jets on the crossflow, axial velocities in the presence of jets measured upstream (x/d=-18.5) and downstream (x/d=6.5) of the actuator are shown in Fig. 7. Ahead of the actuators the velocity profiles of the crossflow are symmetric and uniform at all heights except immediately downstream of the burner (z/d=24) which carried additional flow. The jets clearly did not affect the crossflow velocities at this location. However, downstream of the actuator, the presence of jets significantly altered the crossflow velocities. The jets appear not to influence the crossflow close to the bottom wall. However, higher up, behind the merged jets (at z/d=19 and 24) the flow decelerates, while it accelerates above z/d=24 and close to the walls. Thus, it appears that close to the bottom wall the crossflow can pass between individual jets while near the center of the test chamber, the jets form a bluff body that affects the crossflow. Closer to the top and sidewalls, the crossflow accelerates due to restricted flow passage caused by the merged synthetic jets. This interaction between the synthetic jets and crossflow became more pronounced as the degree of actuation was increased.

Flow and Mixing Visualization

In order to determine whether the improved mixing between the hot and cold streams is indeed due to the wake structure behind the bluff-like body formed by the merging of the four synthetic jets the flow and the resulting mixing were visualized. High speed shadowgrams clearly showed the jets penetrating through the main flow. As the actuation levels were increased, the jet penetration increased. The effect of the jets was also seen to be convected downstream with the speed of the main flow.

Figure 8. Mie Scattering Images – Jets Seeded



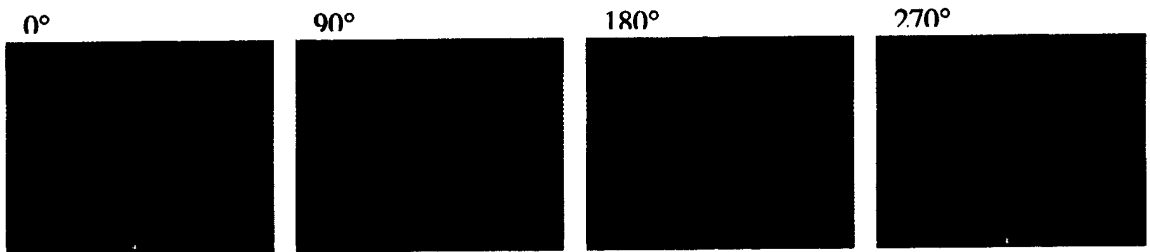


Fig. 1 Mie Scattering Images - Hotflow Seeded

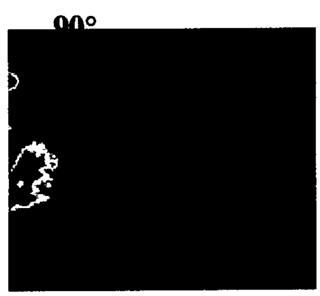


Figure 9. Mie Scattering Image Shows Main Flow Passes around the Jet during the Period of Strongest Blowing

In order to obtain a better understanding of the interaction between the jets and the crossflow different parts of the flow were seeded and the light scattered from a laser sheet was imaged using a high resolution CCD camera. Figure 8 shows the result of seeding only the zero mass flow jets at four instances during the cycle and illuminating the flow with a vertical laser sheet along the test section axis. During the phase of hardest blowing, when the piston has moved halfway up the cylinder (90^0), the jet is virtually undisturbed by the crossflow. Only once the piston has reached top dead center and the blowing has virtually ceased (180^0) is the jet noticeably affected. Figure 9 shows the same situation with the hot flow seeded. Clearly the jets penetrate through the combustor and displace the seeded, hot flow in their paths. This is seen even more clearly in Fig. 10 where the laser beam is parallel to the combustor floor. These images show very clearly that the main flow has to pass around the jet during the period of strongest blowing. This confirms our initial conclusion that the zero mass flow jets enhance mixing between the hot and cold flows by acting as bluff bodies, at least while the pulse jets are blowing.

Conclusions

Dilution zone mixing in a simulated combustor has been manipulated using synthetic, zero mass flow jets. Fractional improvement in mixing based on entropy considerations was used to quantify jets influence on the degree of mixing. Higher actuation produces better mixing, i.e., higher fractional improvement in mixing for all jets investigated. Synthetic jets of circular cross-section produce slightly more enhancements than slots and an orientation normal to the flow produces more efficient mixing than a streamwise orientation. However, the effects of both geometry and orientation are minor. The effect of synthetic jets are frequency independent up to ~140Hz. Fractional improvement in mixing increases significantly for jet to main flow velocity ratio of 2 to 7. The results of velocity mapping and flow and mixing visualizations strongly suggest that the pulsed synthetic jets act as bluff bodies, at least during that part of the cycle when the jet blows strongest. It is the interaction between this "bluff body" and the stratified main flow that facilitates the mixing enhancement.

List of Publications

Non-refereed

"Enhanced Mixing in a Simulated Combustor Using Synthetic Jet Actuators," co-authored with Y. Chen, S. Liang, K. Aung, and A. Glezer. Presented at AIAA 37th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 11-14, 1999.

"Manipulating Pattern Factor Using Synthetic Jet Activators," co-authored with Y. Chen, S. Liang, K. Aung and D. Scarborough. AIAA 2000-0591, 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 10-13, 2000.

Presentations

"Enhanced Mixing in a Simulated Combustor Using Synthetic Jet Actuators," co-authored with Y. Chen, S. Liang, K. Aung, and A. Glezer. Presented at AIAA 37th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 11-14, 1999.

"Manipulating Pattern Factor Using Synthetic Jet Activators," co-authored with Y. Chen, S. Liang, K. Aung and D. Scarborough. AIAA 2000-0591, 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 10-13, 2000.

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Active Control of Compressor Processes

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Problem studied

Analytical and experimental investigation of modeling and control of flow dynamics in axial and centrifugal compressors with the following objectives:

Improved understanding of compressor stall and surge phenomena through modeling, simulation and experimentation.

Investigation of Passive and active control mechanisms for reducing compressor stall and surge

Development of hybrid control methods by combining control-theoretic and decision-theoretic techniques

Summary of most important results:

1. Theoretical Stability Analysis of Compressor Stall with 1-D Actuation

This effort was initiated to fill a gap and discrepancy in the existing literature on the issue of type of feedback needed for active control of compressor stall using 1-D actuation. Previous work by Abed, et al. arrived at the conclusion using bifurcation theory, that only a quadratic feedback of rotating stall amplitude would be effective for stall suppression. Abed's results have since been accepted by the majority of compressor research community as an established fact. Our investigation has clearly established that linear and sub-linear feedback of stall amplitude are equally effective and in fact, such feedback is much superior to quadratic feedback for stall suppression. Further, our findings establish that quadratic feedback of stall amplitude really represents a limit case. We consider our findings to be very fundamental and they remove an existing misconception in the literature on this subject.

2. 2-D Compressor Flow Simulations

Using the 2-D CFD simulation model developed as part of this effort, detailed flow simulations have been carried out to find relevant length and time scales of the flow present during stall transients. These simulations revealed that the neglect of short scale signals - a standing assumption in reduced-order models - appears to be reasonably justified.

3. Extensions to Moore-Greitzer Model

Motivation for this effort came from the known limitations of the current Moore-Greitzer (MG) model in predicting rotating stall frequency. In particular, while MG model predicts rotating stall frequencies to be significantly below 50% of the shaft rotating frequency, the measured rotating stall frequency of the fundamental mode in the axial compressor rig at Georgia Tech is found to be about 60% of the shaft frequency. A close examination of the current MG model development revealed that certain simplifying assumptions with regard to the flow boundary conditions could be the reason for the discrepancy. We have developed a new model taking into account of the correct boundary conditions for the flow in the inlet and outlet ducts. In our extended model we explicitly took the inlet and outlet to be finite and also assumed that there is a certain amount of total pressure loss as the air accelerates from ambient conditions to the entrance to the inlet. Surprisingly, the difference between the Moore-Greitzer model and our extended model is not only quantitative but also qualitative. The first term Galerkin approximation of the Moore-Greitzer model results in two differential equations, governing the amplitude and phase of rotating stall. We have shown, that, for this model, the implicit assumption of infinite inlet and outlet results in axial and circumferential perturbation velocity components at the compressor entrance that evolve under identical dynamics and are always synchronized with each other, with a phase difference of 90 degrees. The first term Galerkin approximation of our model, on the other hand, consists of **two** amplitude and **two** phase equations, one for each of the two velocity components. It predicts, that, exactly **at** rotating stall, the two velocity components are still synchronized with a phase difference predicted by our model (different than 90 degrees), but apart from that they each evolve under their own independent dynamics. It also predicts a slightly higher rotating stall frequency than the one predicted by Moore-Greitzer. This happens to be in better agreement with experimental rotating stall frequency measurements that we have obtained in our lab. For long inlet and outlet ducts, and for zero losses at the entrance to the compressor, our model does reduce to the Moore-Greitzer model. In addition to coming up with this new, explicit model for rotating stall and surge, we have also found a Fourier series solution for the complete perturbation flow field in the inlet and outlet of an infinitely thin compressor annulus. This solution can be used to investigate not only the evolution of rotating stall and surge at the compressor blades, but also the complete transition to these instabilities, over the whole compressor.

Also, in an attempt to improve the compressor performance map needed in our model, we have combined system identification techniques with nonlinear dynamics and bifurcation theory to arrive at a novel identification method.

4. Modeling of Stall in Centrifugal Compressors

A new dynamic model was developed for study of instability dynamics of a centrifugal compressor. The working fluid is approximated as incompressible and inviscid. The compressor is modeled as a cylindrical inlet duct of infinitesimal thickness followed by a perpendicular planar outlet duct also of infinitesimal thickness, with the blade rows located at the junction of the two ducts. The flow in the inlet duct is assumed to be irrotational. For our analysis we use a Fourier series expansion of the periodic dynamical variables along the circumference and solve explicitly for the coefficients. The resulting model is based on the first mode approximation only and incorporates explicitly the nonlinear compressor map. A first implication of our model is that, unlike the case of axial compressors, the vorticity field at the outlet duct plays a significant role in the dynamics of the instabilities developed at the compressor blades in a centrifugal compressor.

5. Experimental Studies on Passive Control of rotating stall

We pursued meaningful passive control schemes (primarily inlet modifications) for suppression of rotating stall. We have come up with a novel inlet modification, which we have experimentally verified to result in significant change to the compressor stall characteristics. In this passive control method, flow separators are placed in the inlet duct so as to block the rotating stall waves. We have evaluated this scheme using the axial compressor rig to demonstrate that the passive scheme is able to alter the compressor flow characteristics so as to make the rotating stall somewhat benign near the stall inception point and hence, aids an active control scheme to be more effective.

6. Analytical and Experimental Study on Active Control of Rotating Stall with Fuel Modulations in the Combustor

The 1D global actuation that underlined previous efforts in active control of rotating stall may in fact be accomplished via combustion modulations. If this is proven to be true, it offers a great advantage to the prospect of advanced gas turbine engine control as various aspects of combustion control such as control of NOx emissions and acoustic-combustion instabilities can be addressed along with compressor control in a single framework. Towards this, we have developed a surge and rotating stall capable model that includes the effects of fuel burning. The new model has been implemented into two different FORTRAN-codes; one for simulation purposes and the other for bifurcation analysis. Our simulation results indicate that active control of fuel burning can be effective in addressing the compressor stall problem. This approach has been evaluated using the axial compressor facility with appropriate modifications to accommodate for fuel burning in the plenum. Using this modified axial compressor facility, we have been able to demonstrate that fuel modulations can have significant effect on rotating stall.

7. Precursor Based Active Control of Stall and Surge

Active control schemes based on rotating stall amplitude feedback depend on the appearance of the instability before any feedback action is taken and hence, are basically reactive in nature. In contrast, a proactive scheme, in which precursors of the impending instability can be used to avoid the instability altogether, will have superior performance as compared to a reactive scheme. A real time observer previously developed at the Georgia Institute of Technology is used to identify the amplitude and frequency of the precursor waves that appear in compressors before and during aerodynamic instabilities. These waves occur both in centrifugal and axial compressors. They appear before the aerodynamics instabilities develop, and persist even after the appearance of the instabilities. The amplitude and frequency of these precursor waves, as identified by the observer are used to generate an alarm signal warning the user that stall and surge are imminent. This alarm signal is used in conjunction with a very simple fuzzy rule based control scheme to recover the compression system out of the instabilities, or to altogether avoid their appearance. This scheme has been implemented on the centrifugal and axial compressor facilities, in conjunction with a throttle control and a fuel flow control, and has been demonstrated to give very promising results.

8. Use of Pressure Transducer Above the Blade Row for Active Stall/Surge Control

In certain compressors that exhibit steep (slope at the stall inception point) stall characteristics, the detection of stall precursors using pressure measurements over the stator may prove to be very ineffective. Using the axial compressor rig, a pressure transducer located in the casing above the blade row has been shown to be much more effective for detection of stall precursors and hence, for active control of stall and surge.

List of Publications

Refereed Papers

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Personnel

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Mihir Lal, Post-Doctoral Fellow

Carlos Rivera, graduate student who received his Ph.D. under this program in 1998

Assad Krichene, received his M.S. and Ph.D. degrees under this program in 1999 and 2001, respectively.

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Sang Bae, received a M.S. degree under this program in 1999.

Soumen Hijra, received a M.S. degree under this program in 2000.

Rungsinee Kasetpibal, M.S. (Graduated in 2001)

Invention Disclosures

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